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CONTRACTOR REPORT ARLCD-CR-79013

TNT EQUIVALENCY TESTING OF CHEMICAL MIXTURES IN CONTINUOUS TNT MANUFACTURING

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Tests were conducted to determine the TNT equivalencies of selected chemical mixtures in their process components from continuous TNT production facilities. This report presents the rationale for selecting the components which were tested, the philosophies used in planning and designing the tests, the designs of the simulated process components and supplementary test equipment, the test procedures, the test results, and analysis of the test results. A methodology was developed to correlate the experimental data quite well and thereby be able		

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18. Supplementary Notes (continued)

Institute at its La Porte Test Facilities, La Porte, Indiana, and at the National Space Technology Laboratory, Bay St. Louis, Mississippi.

20. Abstract (continued)

to predict airblast output produced by other untested process components of similar geometry without additional testing.

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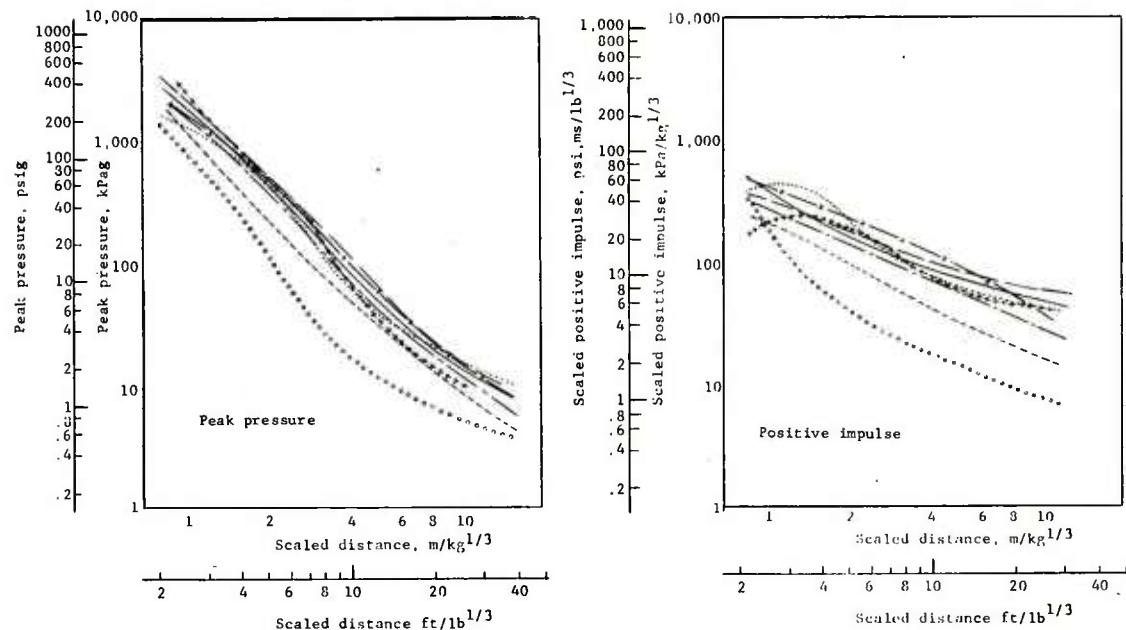
SUMMARY

TNT equivalencies were determined for seven chemical mixtures in their process configurations from continuous TNT production facilities. Blast output was measured and TNT equivalency was computed based on a comparison with the explosive blast output of a surface burst of a hemispherically shaped TNT charge. The results of the program are summarized in the following table and figures.

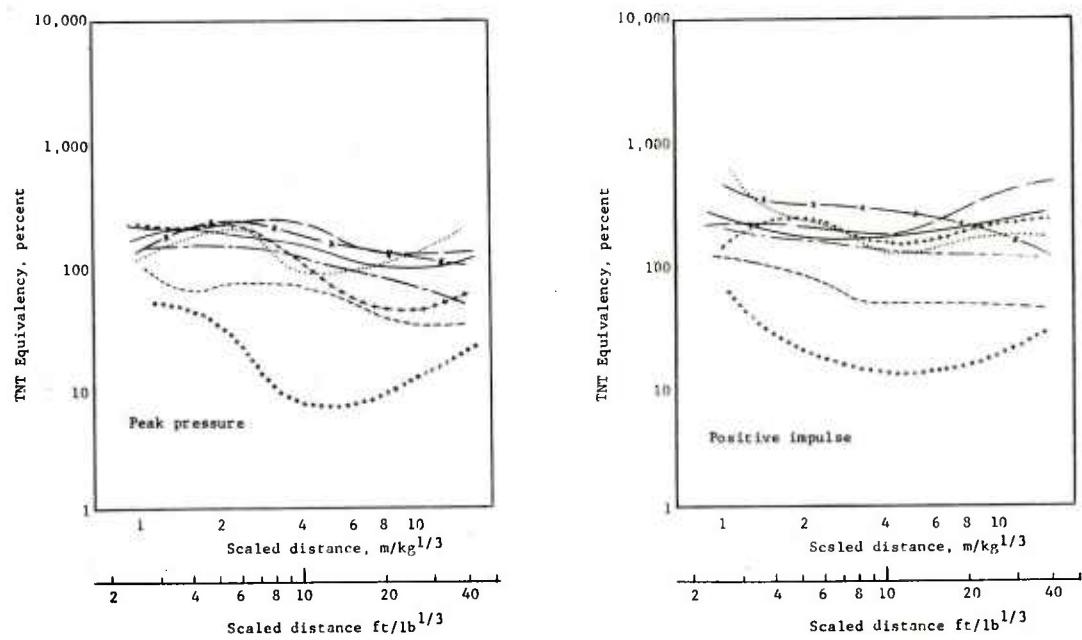
		TNT Equivalency (percent)							
		$\lambda = 1.24 \frac{m}{kg^{1/3}} (3 \frac{ft}{lb^{1/3}})$		$\lambda = 3.67 \frac{m}{kg^{1/3}} (9 \frac{ft}{lb^{1/3}})$		$\lambda = 7.14 \frac{m}{kg^{1/3}} (18 \frac{ft}{lb^{1/3}})$		$\lambda = 15.9 \frac{m}{kg^{1/3}} (40 \frac{ft}{lb^{1/3}})$	
From Raiford System	Component	P	I	P	I	P	I	P	I
	Nitrator 3A	185	229	158	165	98	193	112	264
	Nitrator 6	204	215	244	179	132	255	127	476
	Separator 6 (north)	134	480	99	138	98	147	202	173
	Separator 6 (east)	213	170	137	151	48	138	55	228
	Acid Wash Tank (predicted)	142	176	128	131	86	115	50	109
	Sellite Wash Tank	82	108	70	48	42	47	32	43
From Planned System Utilizing Dynamic Separators	Nitrator 4	168	387	189	274	132	223	98	114
	Nitrator 8	49	47	8	13	8	13	19	26

Key for figures on following page

—————	Nitrator 3A
— — — — —	Nitrator 6
· · · · ·	Separator 6 (north gages)
++ + + + + +	Separator 6 (east gages)
— — — — —	Acid Wash (predicted)
- - - - -	Sellite Wash
— x — x —	Nitrator 4
o o o o o o o o	Nitrator 8

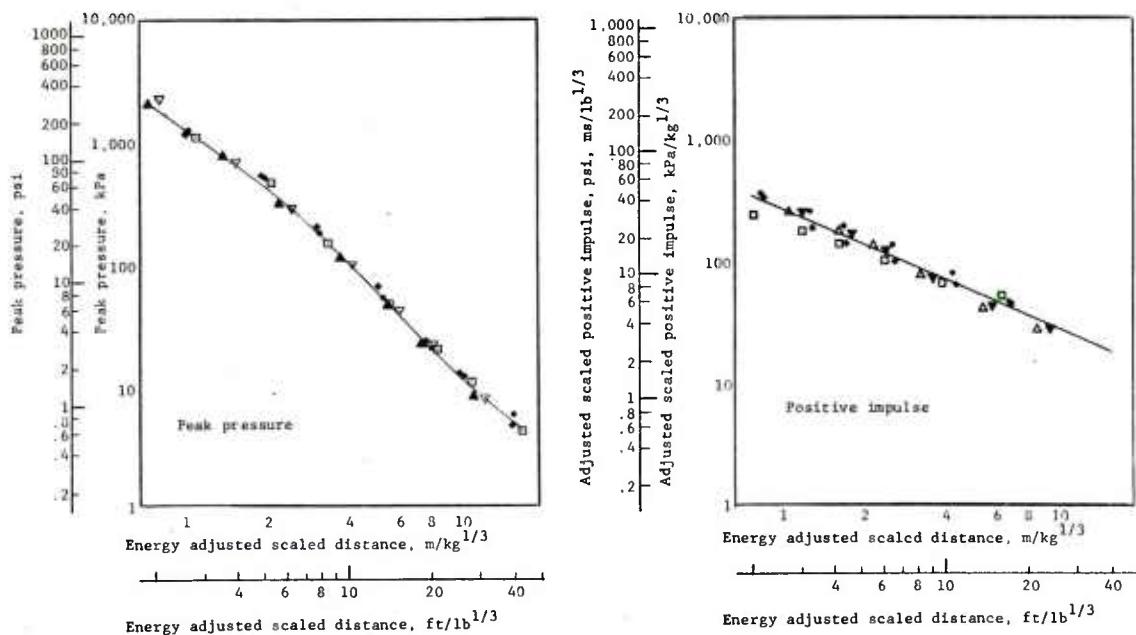


SUMMARY OF PEAK PRESSURE AND SCALED IMPULSE DATA



SUMMARY OF TNT EQUIVALENCIES

A technique was developed to predict the airblast output and TNT equivalencies produced by a wide variety of chemical mixtures in similar configurations using a limited amount of experimental data and thus minimizing the number of experiments required. The technique relies on correlating the experimental data by applying an "energy equivalency" to the explosive mass. The experimental data from all the cylindrical configurations condenses quite nicely onto single peak overpressure and scaled positive impulse curves.



CORRELATION OF EXPERIMENTAL DATA

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1. INTRODUCTION

1.1 Background

On May 31, 1974, an accidental explosion occurred at the Radford Army Ammunition Plant (RAAP) continuous TNT¹ production line (reference 1). Considerable damage was sustained due to the high TNT and detonable nitrobody content of in-process materials. Initially, there was an indication that more energy was released in the blast than could be accounted for by the quantities of TNT and other detonable nitro bodies present (reference 2). Perhaps the acid could be contributing to the explosive output in some way.

To reduce the quantity of explosive materials present in a reconstructed line, it is intended to utilize dynamic separators in lieu of the slower acting gravity separators which were previously in the RAAP continuous TNT line. This change should reduce the total TNT content in the Nitration and Purification Building from 8740 kg (19,250 lb) to a nominal 4310 kg (9500 lb) (reference 3).

1.2 Program Objectives

The program described in this report was designed to determine the explosive airblast output (in terms of TNT equivalency²) of selected components present in the "old"³ RAAP TNT production line and the planned "new"³ line which will utilize dynamic separators. The components which were selected from the old RAAP system are shown in figure 1 in their locations in the Nitration and Purification Building. These components

¹ Trinitrotoluene

² The concept of TNT equivalency is discussed in Appendix B. Pressure TNT equivalency is defined as the ratio of TNT weight to test explosive weight (X100%) that will produce the same peak overpressure at the same radial distance for both charges. Similarly, impulse equivalency is the ratio of TNT weight to test explosive weight which will produce the same impulse at the same radial distance. The standard TNT charge for comparison is always a hemisphere placed on a rigid surface at ground level.

³ In this report the prefix "old" refers to the continuous TNT production line utilizing gravity separators involved in the RAAP explosion, whereas the prefix "new" refers to the planned continuous TNT line utilizing dynamic separators.

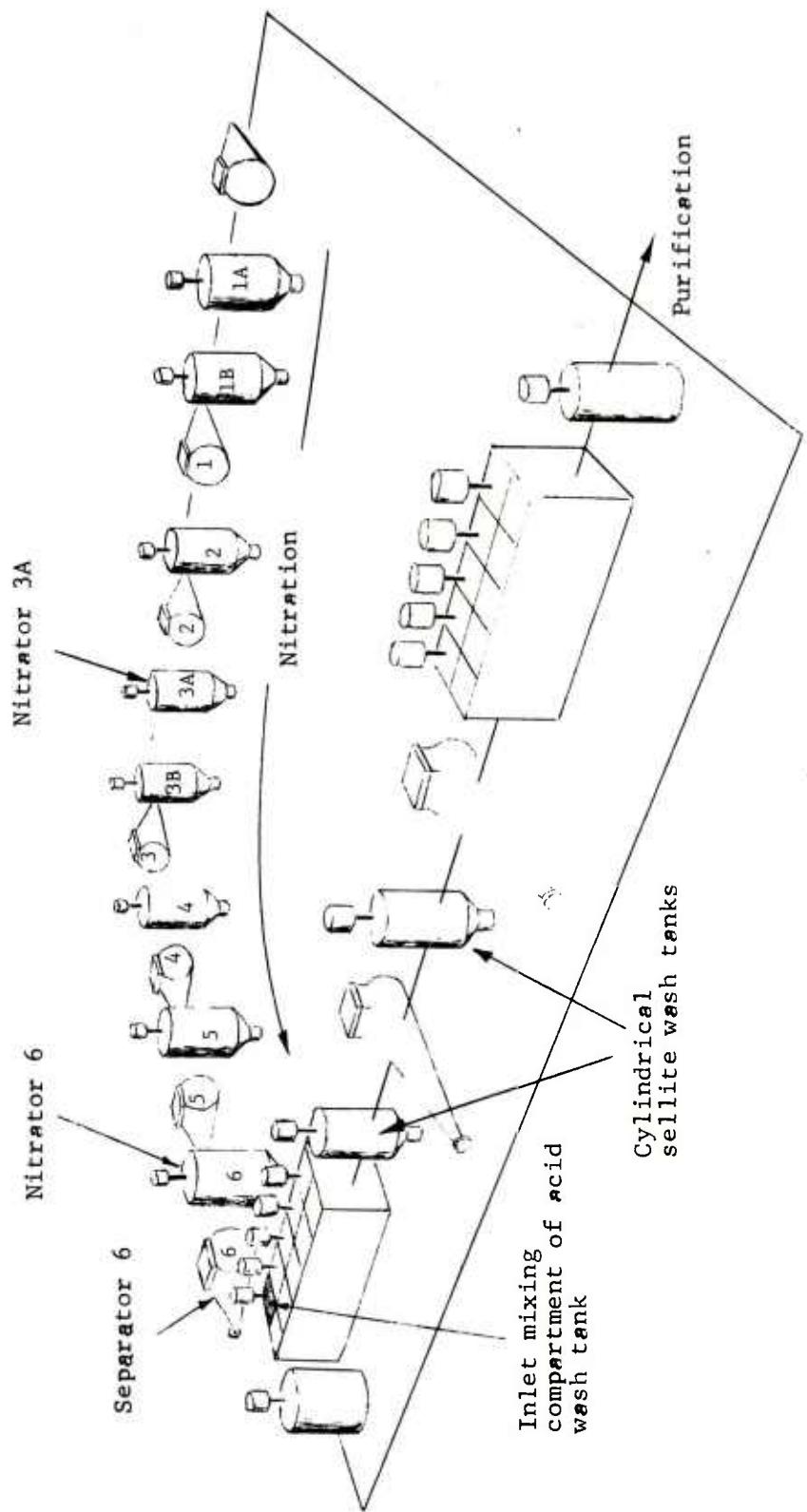


Fig 1 TNT nitration and purification building

are nitrator 3A, nitrator 6, separator 6, a sellite wash tank, and the inlet mixing compartment of the acid wash tank. Three nitrators were originally selected for the new system utilizing dynamic separators: nitrator 4, nitrator 5 and nitrator 8. Nitrator 4 is functionally similar to old nitrator 3A and nitrator 8 is functionally similar to old nitrator 6. Nitrator 5 was selected to be tested only if nitrator 4 did not detonate. Since nitrator 4 detonated in the first trial, nitrator 5 was not tested.

1.3 Report Organization

In section 2 of this report the experimental system designs are described in a fair amount of detail. The section is divided into three parts. The first part presents the philosophies used in (a) selecting the general program approach, (b) selecting the components to be tested, (c) producing the chemical mixtures, and (d) scaling. The second part describes the total system design used in the original program tests. These tests were conducted at the IIT Research Institute (IITRI) facility at Kingsbury Ordnance Plant (KOP) near LaPorte, Indiana. The explosive limit for that test site is approximately 22.7 kg (50 lb) of TNT or equivalent. In designing the KOP tests, 22.7 kg (50 lb) of nitrobody (TNT and DNT⁴) were allowed per shot. The results of these small-scale tests indicated that the 22.7 kg (50 lb) size was at or near the threshold for detonation for most of the components tested (see sections 4 and 5). Therefore it was decided that scaling should be verified by conducting tests at a larger size. Such tests were planned, designed, and constructed primarily by IITRI personnel for execution at Edgewood Arsenal Resident Laboratory at the National Space Technology Laboratories (NSTL) near Bay Saint Louis, Mississippi. These tests were for 90.8 kg (200 lb) of TNT and DNT per system. This corresponds to about one-tenth scale for nitrator 6. Due to an unfortunate series of operational problems at NSTL only one large-scale test was successfully completed. Because the major product of the large-scale test effort was consequently the system design, the design is presented in detail in the third part of section 2.

⁴Dinitrotoluene

In section 3, the general test plan and procedures are presented for the small-scale (22.7 kg, 50 lb size) and the large-scale (90.8 kg, 200 lb size) test efforts. Test results are presented in section 4 and analyzed in section 5. A technique for predicting TNT equivalency of chemical mixtures in their process configuration using limited test data is described and used to predict peak overpressure, scaled positive impulse and TNT equivalencies for the acid wash tank compartment, for which the experimental data generated in this program were not adequate. The implications of the results of this program are discussed.

2. DESIGN OF THE EXPERIMENTS

2.1 Preliminary Investigations and Decisions

Prior to conducting the tests described in this report, a considerable amount of planning had to be done. The components tested are physically quite complex. Many of them are agitated and have complex internal geometries. The chemical mixtures present contain nitro bodies (TNT and DNT) dispersed as oil droplets (or settled in a layer) and dissolved in nitrating acid or wash solution. Most of the systems are agitated. Many trace compounds are present which probably do not have a significant influence on blast energy released but could have a significant influence on sensitivity (i.e., whether or not detonation can be initiated). Before the test program could be developed, many decisions had to be made and philosophies defined.

2.1.1 Selection of General Approaches for Simulating the Chemical Mixtures

Four approaches were evaluated for producing the chemical mixtures to be tested in the scaled model system components:

1. Extract chemicals from an active TNT line, such as at Joliet AAP or Volunteer AAP.
2. Use cold nitrating acid and solid TNT flakes dispersed in the acid.
3. Use nitrating acid at the proper process temperature and pure liquid TNT dispersed and allowed to partially dissolve in the acid.
4. Use nitrating acid at the proper process temperature, pure liquid TNT dispersed and allowed to partially dissolve in the acid, and liquid DNT extracted from the Joliet AAP TNT line.

Option 1 clearly would be the most realistic if it could be accomplished safely without significantly altering the chemical compositions. The major advantage of this approach was the inclusion of trace compounds which could not be reproduced simply and accurately in a batch. Both Joliet AAP and Volunteer AAP were visited to discuss and evaluate this approach. For upstream nitration reactors, such as nitrator 3A, the chemical mixtures are quite reactive. To stop the reaction for shipping chemicals to the IITRI test site, the chemicals would have to be extracted from the adjacent gravity separator and frozen quickly. At the IITRI test site, they would have to be melted, transferred to the model reactor, and detonated quickly to avoid excessive continued reaction and a possible premature fire or explosion. There was no way to use this approach for tests related to the new dynamic separator system because that system is not in operation at the present time. Because of the many complexities and hazards of this approach, it was eliminated from contention.

Option 2 clearly provided the most unrealistic simulation of the real system but it might be the simplest and safest approach to accomplish. No trace compounds would be present. Nitro bodies would not be dissolved in the acid phase and the resultant intimate contact for reaction would be lost. It would be difficult if not impossible to properly disperse the solid TNT flakes in the acid. The flakes would get caught in the mock cooling coils and block flow. The flakes would disperse differently than liquid droplets in the acid and produce a wrong internal geometry. Because of all these inaccuracies, it is likely that some important phenomenon would have been lost in the testing and the test program would have been made meaningless. Therefore, this approach was not used.

Option 3 was to use nitrating acid at the proper temperature and liquid TNT dispersed in the acid. This was the approach used for most of the tests conducted. It was used for all systems which were basically nonreacting (all systems except old nitrator 3A and new nitrator 4). In all cases, the liquid TNT was added to the acid or wash solution well before the initiation (on the order of an hour in most cases) and agitated to assure that some TNT became dissolved.

Option 4 was used for old nitrator 3A and new nitrator 4. Option 4 was to simulate the composition in reactive components using a batch process to make TNT in the field. Rather than start with raw toluene, a shortcut was taken by adding a mixture of TNT and DNT to nitrating acid.

Small scale experiments were conducted early in the program to determine the reaction time required to reach the desired compositions in nitrators 3A, 4 and 5. In each case a proper nitrating acid was mixed and brought to the continuous process reaction temperature. An amount of liquid TNT less than the desired quantity was then added to the acid. Then an amount of DNT greater than the desired quantity was added. As the DNT to TNT nitration progressed, samples were extracted and analyzed. Temperature was maintained constant during the experiments using cooling coils. In this way the required reaction time for each reactive nitrator test was determined. The DNT used in the TNT equivalency field tests was extracted from the Joliet Arsenal continuous TNT line in crude form. Crude DNT was used in an attempt to add realism to the chemical mixture by maintaining some of the trace compounds present in the actual system.

2.1.2 Selection of Components to be Tested

As previously noted, five system components were selected from the old RAAP continuous TNT line (nitrators 3A and 6, separator 6, a sellite wash tank, and a mixing compartment of the acid wash tank). Three components were originally selected from the new system incorporating dynamics separators (nitrators 4, 5 and 8). Old nitrator 3A was selected because the explosion at RAAP was initiated at or near this reactor. An operator was using a rubber hose to clean white compound out of the pipe connecting separator 2 to nitrator 3A when the hose apparently got caught in the agitator and pulled into nitrator 3A. The temperature rose in parts of the nitrator but it is difficult to say if the nitrator detonated first or merely initiated, for example, TNT is an adjacent gravity separator. Since nitrator 3A was where the problem began, it was unique and worthwhile testing. Nitrator 3A was simulated using a batch process nitrating DNT to form TNT as described above (option 4).

Nitrator 6 was selected for two reasons. First, it contains the highest concentration of TNT of the nitrators and was considered to be a probable worst case for that reason. Second, because it contains almost no DNT, the nitrobody composition could be simulated quite well by using pure TNT, making the tests simpler.

Separator 6 has essentially the same composition as nitrator 6 and was therefore the separator selected for testing. A separator was tested for two reasons. The chemical mixture is in the settled state with a layer of liquid TNT floating on a layer of acid with some TNT dissolved in the acid. In addition, the component geometry is quite

different from the reactors. In the tests, the separator was simulated by a box with no coils or agitator inside. A set of heating coils and an agitator were temporarily mounted on the box cover to prepare the chemical mixture. These were removed prior to initiation.

A sellite wash tank was selected to evaluate the effect of replacing the nitrating acid by water in a similar cylindrical tank configuration with coils inside. The acid wash tank was selected because it is a large tank containing a very high TNT content.

New nitrators 4 and 8 serve functions parallel to old nitrators 3A and 6 respectively. These were evaluated to help gauge safety improvements represented by the new design utilizing dynamic separators. If nitrator 4 did not detonate, nitrator 5 was to be tested. Nitrator 5 contains a slightly higher TNT concentration and was originally thought to be more easily detonable for that reason. Since nitrator 4 detonated in the first trial, nitrator 5 was not tested.

2.1.3 Design of the Batch Process

Nitrators 3A(old), 4(new) and 5(new) are all quite reactive systems containing from 4 to 16 percent DNT by weight. These systems could not be simulated with confidence by replacing all nitrobody by TNT. Therefore, a batch process was used to make TNT in the field and simulate the compositions in the more active nitration reactors. When the batch composition was approximately equal to the composition present in the continuous process reactor, detonation of the booster was initiated.

To determine the proper detonation time for these tests, small scale experiments were conducted. One test was completed for each of the three reactors with a duplication run for nitrator 4.

The equipment used for the laboratory runs consisted of a small polypropylene reactor, an electrical laboratory mixer with a stainless steel agitator shaft, and a 0.64 cm (0.25 inch) O.D. stainless steel tubing wound into a coil was used to cool the reactor. The experimental procedure for each of the runs was as follows:

- The reaction acid was prepared at IITRI by mixing the appropriate quantities of 65 percent oleum, 67 percent nitric acid and 71 percent nitric acid. Sufficient acid was made for two experimental runs of nitrator 4 and one each of nitrators 5 and 3A.

- At KOP test site, the pre-mixed nitration acid was heated to about 85°C (184°F) and the appropriate amounts of DNT and TNT were weighed and melted in a hot water bath.
- The hot acid was added to the polypropylene reactor, agitated, and then the melted TNT was added.
- The reaction mixture was then cooled by the internal cooling coils to about 77°C (170°F) for nitrators 4 and 8 and maintained at 85°C (184°F) for nitrator 3A.
- The time was recorded and the melted DNT was added into the reactor.
- The reaction was sampled by removing 0.5-1.0 cc (0.03-0.06 inch³) of the reaction mixture with a syringe and injecting the sample into 55 cc (3.36 inch³) of distilled water.
- The samples were analyzed at IITRI by gas chromatography to determine the relative amounts of DNT and TNT.

A summary of the small-scale chemistry experimental results is presented in table 1. In each case, the starting composition, target detonation composition and required reaction duration is given. An 85°C (184°F) reaction temperature was required for nitrator 3A to prevent crystallization of TNT at 77°C (170°F).

Figure 2 shows the nitrobody weight percent of DNT as a function of time in the two nitrator 4 runs. This is the weight of DNT divided by the total nitrobody (TNT and DNT) weight multiplied by 100 percent. The target value for nitrator 4 was 37.4 weight percent DNT. The discrepancy in results between the two laboratory runs (9.5 and 7 minutes required from runs 1 and 4 respectively) was attributable to equipment difficulties during run 4. In run 1, the temperature was closely controlled between 75° and 80°C (166° and 175°F) for the first 5 minutes, whereas the temperature ranged between 75° and 90°C (166° and 193°F) in run 4. Even with the difference in reaction temperatures, the detonation compositions were within 10 weight percent DNT at 9.5 minutes of reaction time.

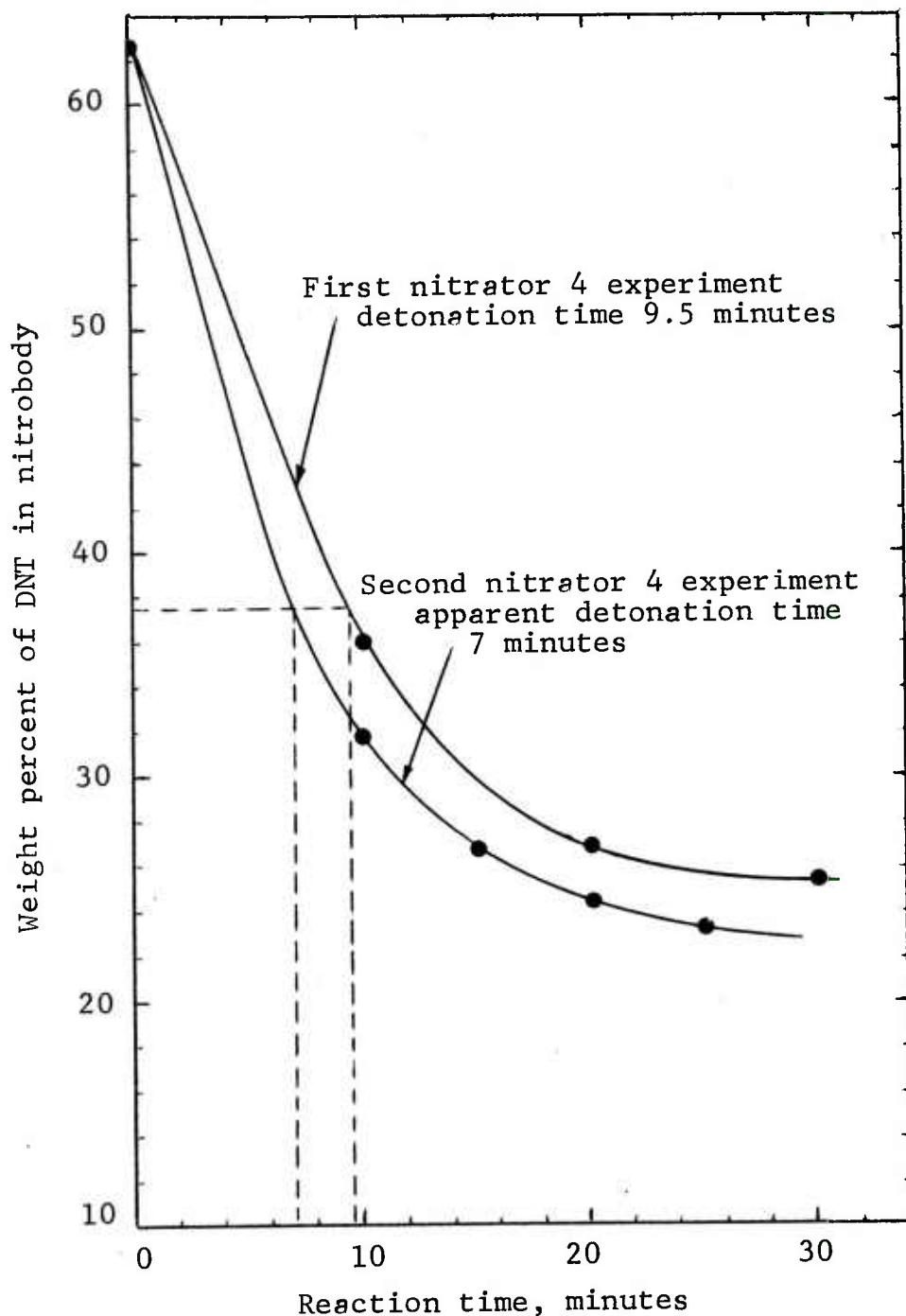


Fig 2 Weight percent DNT versus reaction time for nitrator 4

Table 1
Summary of small-scale chemistry experiments

System	Starting composition (weight %)	Target detonation composition (weight %)	Required reaction duration for field tests
old nitrator 3A	23.0% DNT	16.6% DNT	2.5 minutes (adjusted to 3 minutes to account for DNT drop time) at 85°C (184°F)*
	24.0% TNT	32.0% TNT	
	9.3% HNO ₃	7.0% HNO ₃	
	34.5% H ₂ SO ₄	38.0% H ₂ SO ₄	
	9.2% SO ₃	6.4% SO ₃	
new nitrator 4	14.2% DNT	9.0% DNT	9.5 minutes (adjusted to 10 minutes to account for DNT drop time) at 77°C (170°F)
	8.5% TNT	15.0% TNT	
	9.8% HNO ₃	8.0% HNO ₃	
	57.2% H ₂ SO ₄	60.0% H ₂ SO ₄	
	10.3% SO ₃	8.0% SO ₃	
new nitrator 5	10.0% DNT	4.0% DNT	6.5 minutes (adjusted to 7 minutes to account for DNT drop time) at 77°C (170°F)
	9.5% TNT	17.0% TNT	
	12.1% HNO ₃	10.0% HNO ₃	
	48.8% H ₂ SO ₄	52.0% H ₂ SO ₄	
	19.6% SO ₃	17.0% SO ₃	

*In nitrator 3A, 85°C (184°F) was required to keep the TNT in the liquid state in the small-scale experiments.

Figure 3 shows the nitrobody weight percent of DNT versus time for nitrators 3A and 5. Nitrator 3A was found to require a 2.5 minute reaction time and nitrator 5 required a 6.5 minute reaction time. In the large-scale experiments it took about 2 minutes to transfer the liquid DNT from the drop tank into the model reactor. To approximately compensate for this DNT transfer time, 30 seconds was added to each of the reaction times which were determined from the small-scale chemistry experiments.

In the large-scale TNT equivalency tests, the same procedure used in the small-scale experiments was followed. That is, the initial nitration acid was accurately mixed and weighed into containers at IITRI, Chicago. Sufficient acid was made for several detonations and therefore each batch of nitration acid was identical for a series of shots. The nitration acid was heated in the test reactor at the detonation site. After heating the acid, liquid TNT was added to the agitated reactor. The DNT was melted and placed in an

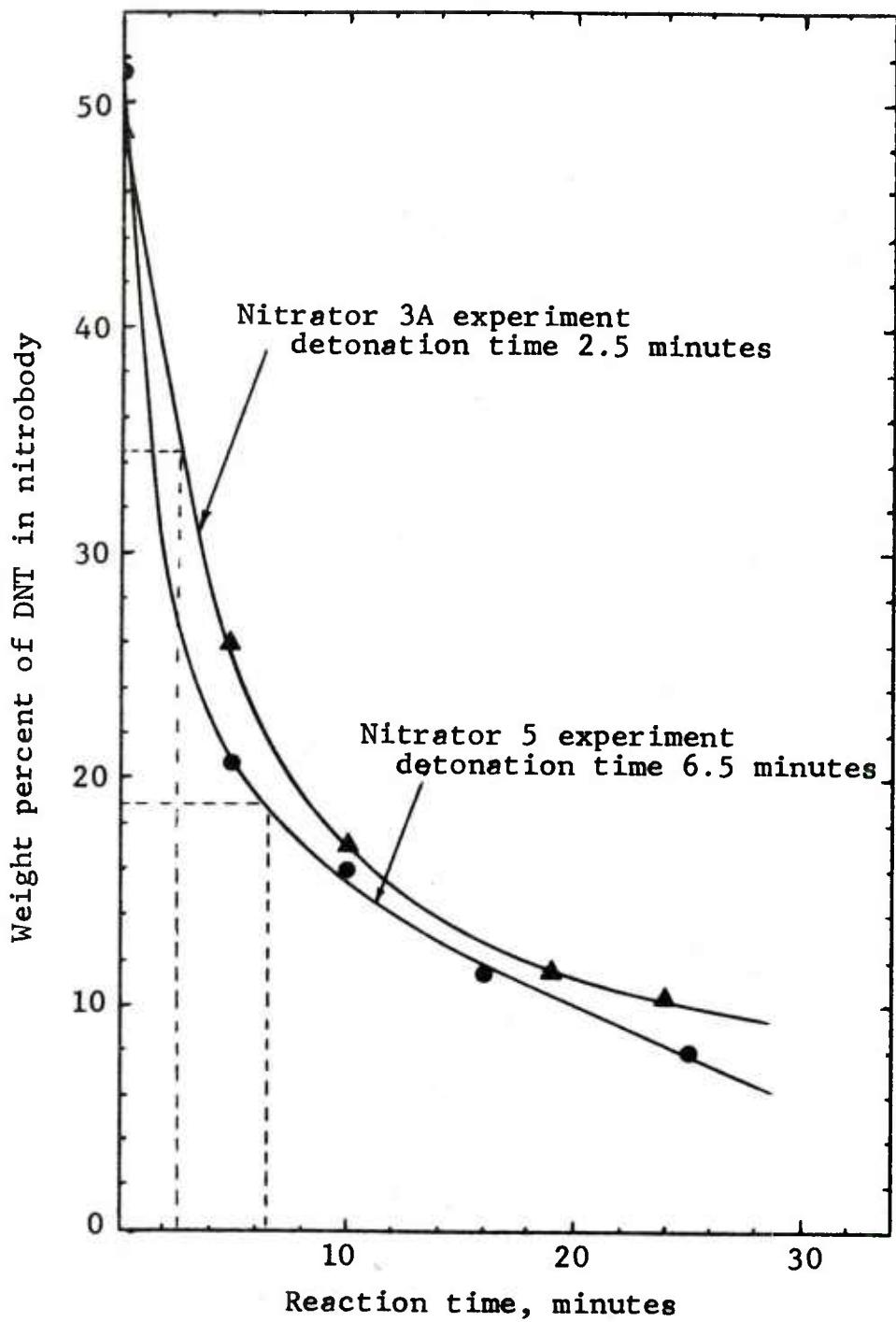


Fig 3 Weight percent DNT versus reaction time for nitrators 3A and 5

overhead reservoir (the DNT drop tank) with the addition controlled by a solenoid valve. At time zero the solenoid valve was opened and all the liquid DNT was allowed to flow into the reactor. At the predetermined time after the start of the DNT addition, an explosive booster in contact with the tank bottom was detonated.

2.1.4 Scaling Philosophy

2.1.4.1 General Considerations

Correlation of experimental data is generally accomplished using dimensionless groups derived by conducting a dimensional analysis on the experimental parameters or the equations governing the phenomenon being studied. Several investigators (Hopkinson, Sachs, Lutzky and Leto, Baker, Doering and Burkhardt, Brown, etc.) have developed such scaling laws for explosive airblast output. Hopkinson scaling is the most common form and is used for presentation of data in section 4 of this report. Hopkinson, or "cube root", scaling presents peak overpressure (P), scaled positive phase duration ($\tau/W^{1/3}$), and scaled impulse ($I/W^{1/3}$) in terms of scaled distance ($R/W^{1/3}$), where τ is positive phase duration, I is impulse, R is distance from the blast center, and W is the explosive weight. The explosive weight represents the total energy of the blast source, E , and W can be replaced by E in the scaling relations. Hopkinson scaling strictly only applies to blast waves produced by sources of the same explosive material in the same atmospheres with geometric similarity conserved. In section 5, it will be shown that replacing W by E in the Hopkinson scaling parameters largely accounts for differences in the TNT process vessel chemical composition and correlates the data quite well. Many other factors not considered in Hopkinson and other commonly used blast wave scaling laws can also significantly affect the airblast output produced. These factors are summarized in table 2 under four categories: (a) amount of energy released, (b) rate of energy release, (c) configuration and (d) ambient conditions. These factors were considered in designing the experiments to maintain the most important features of the system design.

Table 2
Explosive airblast output significant factors

(a) AMOUNT OF ENERGY RELEASED

- Chemical energy released in detonation
- Oxygen balance and potential for afterburning
- Amount of water in detonation products in comparison to usual explosives (effect on ratio of specific heats -- reference 4)
- Expected confinement influence (too much confinement absorbs energy while too little confinement allows spalling or may prevent the development of detonation)
- Critical explosive weight
- Critical explosive dimension
- Critical booster size
- Unusual reaction kinetics

(b) RATE OF ENERGY RELEASE

- Reaction duration $\sim \frac{\text{Characteristic Dimension}}{\text{Detonation Velocity}}$

(c) CONFIGURATION

- Energy density
- Charge shape
- Internal charge geometry
- Charge orientation
- Booster location
- Ground reflectivity
- Height of burst

(d) AMBIENT CONDITIONS

- Pressure
- Speed of sound (or temperature)

2.1.4.2 Chemical Composition Related to Scaling

As discussed in sections 2.1.1 and 2.1.3, considerable emphasis was placed on closely simulating the chemical mixtures found in the full-scale continuous process TNT manufacturing facilities. A comparison of the actual and "mock" chemical mixtures for each component tested is provided in table 3. Reproducing the composition was important to assure that the chemical energy released in a detonation per unit weight of material would be independent of the scale. In addition, the reaction kinetics, available oxygen and reaction products would be the same as in a full-scale system.

Table 3

Weight composition of major constituents
for TNT process components being evaluated
(all values are weight percents)

Test series	DNT	TNT	TNB	TNBA	HNO ₃	H ₂ SO ₄	HNOSO ₂	H ₂ O	SO ₃
1. Nitrator 3A									
Actual	16.22	31.27	0.001 (trace)	0.001 (trace)	6.82	36.98	2.44	0	6.27
Mock	16.6	32.0	0	0	7.0	38.0	0	0	6.4
2. Nitrator 6									
Actual	0.15	38.01	0.002 (trace)	0.01	8.93	33.48	0.11	0	19.31
Mock	0	38.0	0	0	9.0	33.5	0	0	19.5
3. Separator 6									
Actual	0	38.16	(trace)	0.01	8.9	33.48	0.11	0	19.31
Mock	0	38.0	0	0	9.0	33.5	0	0	19.5
4. Acid Wash									
Actual	0	85.00	0	0	0.74	1.31	0.20	12.75 (yellow water)	0
Mock*	0	53.12	0	0	3.33	4.83	0	38.72	0
5. Sellite Wash									
Actual	0	49.00	0	0	0	0	0	51.00 Red Water (H ₂ O/Sellite)	0
Mock	0	49.0	0	0	0	0	0	51.0	0
6. Nitrator 4									
Actual	8.55	14.03	0	0	7.80	57.01	5.41	0	7.2
Mock	9.0	15.0	0	0	8.0	60.0	0	0	8.0
7. Nitrator 5									
Actual	3.87	16.59	0	0	9.62	50.74	2.65	0	16.53
Mock	4.0	17.0	0	0	10.0	52.0	0	0	17.0
8. Nitrator 8									
Actual	0.02	21.86	0	0	11.44	41.76	0.05	0	24.57
Mock	0	21.9	0	0	11.44	41.8	0	0	24.6

* The composition tested in the acid wash tank series was incorrectly mixed, as discussed in a subsequent section of this report.

Crude DNT was even used for reactive tests to introduce trace compound which might have an effect on sensitivity to initiation. By closely approximating the chemical composition, both reaction duration (or detonation velocity) and energy density would also be maintained in the scaled model components.

2.1.4.3 Explosive Mass Scaling

IITRI's explosive test facility near LaPorte, Indiana has a limit of approximately 22.7 kg (50 lb) of TNT or equivalent per test. Early in the program it was decided to scale down the test components from full-scale so that 22.7 kg (50 lb) of nitrobody would be present in each test. The nitrobody consists of TNT and DNT dispersed and in solution in each system. For each component to be tested, the mass of nitrobody (M_n) in the full-scale system was determined from references 5 and 6. Since the mass density of the chemical mixture is independent of scale, a volume scaling factor (η_v) could be determined using relation:

$$\eta_v = \frac{22.7 \text{ kg}}{M_n \text{ kg}} \text{ or } \frac{50 \text{ lb}}{M_n \text{ lb}}$$

To scale down the geometry of each system so that it contained 22.7 kg (50 lb) of nitrobody, each linear dimension was multiplied by a linear scale factor η_l , where

$$\eta_l = \eta_v^{1/3}$$

Similarly, for the 90.8 kg (200 lb) tests, the volume scale factor was defined as

$$\eta_v = \frac{90.8 \text{ kg}}{M_n \text{ kg}} \text{ or } \frac{200 \text{ lb}}{M_n \text{ lb}}$$

and the linear scale factor η'_l was computed from

$$\eta'_l = (\eta'_v)^{1/3}$$

The scaling factors used in designing the test components are summarized in table 4. These exact scaling factors guided the design of the test components, but practical considerations such as available sheet metal thicknesses, available coil wire sizes, and simplifications to reduce cost and increase ease of fabrication dictated the exact dimensions of the mock system components.

Table 4
Summary of scale factors used in design

System Component	Small-scale tests 22.7 kg (50 lb)		Large-scale tests 90.8 kg (200 lb)	
	η_v	η_ℓ	η'_v	η'_ℓ
Old nitrator 3A	0.0214	0.2777	--	--
Old nitrator 6	0.0241	0.289	0.0964	0.459
Old separator 6	0.093	0.453	--	--
Old sellite wash tank	0.0571	0.385	--	--
Old acid wash tank	0.331	0.692	1.0	1.0
New nitrator 4	0.0375	0.335	0.150	0.531
New nitrator 5	0.038	0.336	--	--
New nitrator 8	0.035	0.327	0.140	0.519

2.1.4.4 Confinement Scaling

As noted in table 2, too much confinement will absorb and reduce the blast output, and too little confinement may prevent the occurrence of detonation or allow unreacted material to be thrown off (e.g., spalling in solid materials). In most TNT equivalency test programs, the configuration is relatively simple. A container holds the explosive within its walls. In these situations, confinement is scaled by keeping the wall mass to explosive mass in a constant ratio, i.e., multiplying the wall thickness by the linear scale factor (η_ℓ or η'_ℓ).

Most of the continuous TNT process components evaluated in this program have much more complex confinement. The outer tank wall is only one portion of the total confinement present. Within the tank wall, several rows of tightly packed spiral wound cooling coils are present in many of the tanks. Within the coils is another layer of metal, the draft tube. The cooling coils contain a significant mass of metal which can absorb energy or confine a developing detonation and allow it to propagate into a full detonation.

Ideally, the overall confinement of such a complex system could be scaled by applying the proper linear scale factor to the outer tank wall thickness, the draft tube wall thickness, and the coil geometry (tube ID, tube OD, coil length, and pitch). The coils should also be filled with liquid of the same density as the heat transfer fluid used

in the full-scale system. Due to practical constraints, this could not be accomplished precisely for the mock components in this program. The first constraint was that steel tubing to fabricate the coils had to be purchased in a bulk quantity. The selected tubing diameter approximated the scaled diameter for all the 22.7 kg (50 lb) systems, but was not exact for any of them. Only two of the spiral coils were active in each nitration reactor tested. These were filled with water, while the remaining four coils were crimped closed at each end and contained air. In all cases, the coil volume (and displaced liquid volume) was scaled properly from the full-scale system design. Thus, the liquid level inside the tank was scaled properly, but exact internal geometry and coil (plus heat transfer fluid) mass were only approximately scaled.

2.1.4.5 Agitation Scaling

It was not sufficient to test the correct chemical composition inside each system component. The chemical mixture consists of an oil phase containing liquid nitrobodies (TNT and DNT) dispersed in an acid or wash solution. The acid or wash solution also contains dissolved nitrobodies. To scale the mixing action from the full-scale system in order to simulate droplet size distributions and flow patterns, agitator revolutions per minute (rpm) was selected to produce the same impeller tip speed as exists in the full-scale system. This approximately reproduces the flow velocity in the draft tube (volume flow rate per unit area) and the maximum shear action in the liquid at the tip of the impeller blade. If the impeller blade geometry were scaled directly for each full-scale system, mixing action would be reproduced in the model components quite well. Impeller geometry was not scaled for each system. A commercially available propeller quite similar to that used in the sellite wash tank was used in all tests. Therefore, mixing action was only approximately reproduced in most of the tests.

2.1.5 Total Test Arrangement

The detailed system design is presented in section 2,2 for the 22.7 kg (50 lb) size and in section 2,3 for the 90.8 kg (200 lb) size. Each test consisted of a scaled TNT process component, a heating/cooling system, a TNT and DNT melt/pour system, the test site, and instrumentation. The scaled component was a tank with a cover and in most cases a draft tube, coils, and an agitator. Some of the coils were active, used to heat the acid or wash solution above the melting point of TNT and to establish the proper mixture temperature for the test. The heating/cooling system provided hot and cold water to the active coils. Liquid TNT

and/or DNT was prepared for each test and transferred into the test component at the proper time. The test component was set up in the field with pressure transducers located at a range of distances from the explosion center. Chemical mixture temperature, rpm, and detonation velocity were measured. The total test arrangement for each system is described in detail in the following sections.

2.2 Design of Small-Scale 22.7 kg (50 lb) Experiments

Test conducted at the IITRI explosive test facility were designed so that 22.7 kg (50 lb) of nitrobody was involved in each test. This explosive weight is the test site approximate limitation. The mock TNT process components, instrumentation, and support equipment for these tests are described.

2.2.1 Design of Mock TNT Process Components

Seven TNT process components were evaluated in this test program. These are old nitrator 3A, old nitrator 6, old separator 6, old acid wash tank mixing compartment, old sellite wash tank, new nitrator 4, and new nitrator 8. Construction drawings for these systems were provided by ARRADCOM and the mock components were scaled from these drawings. The reference construction drawings are given in table 5.

The nitration reactors and sellite wash tank were cylindrical vessels with a cover, draft tube, agitator, and heat transfer coils. The separator and acid wash tank were rectangular box-shaped components. A schematic representation of the cylindrical components is shown in figure 4. The dimensions of the 22.7 kg (50 lb) size scaled system are presented in table 6. Each system consisted of four basic parts: (a) a cylindrical outer vessel, (b) a cover and draft tube assembly, (c) an agitator assembly, and (d) a set of heat transfer coils.

2.2.1.1 The Cylindrical Outer Vessel

The vessel was fabricated from 0.159 cm (1/16 inch) thick carbon steel sheet. The seam and bottom edge were welded to prevent leakage of the acid/nitrobody mixture during the tests. Two chromel alumel thermocouples penetrated the tank wall through small holes. One was at the midheight of the tank and the other was just above the tank bottom. The base of each thermocouple was sealed with Hysol epoxy to prevent an acid leak.

Table 5

Relevant construction drawings referenced in nitrobody process component scaledown

<u>Component type</u>	<u>Coil design</u>	<u>Container</u>	<u>Draft tube</u>	<u>Impellar</u>
Nitrator 3A (N-3A)	HRP-37-12837 HRP-37-12899	HRP-37-12837 HRP-37-12888	HRP-37-12883	HRP-37-13148
Nitrator 4 (N-4)	ACI-P5510 ACI-P5515	ACI-P5510 ACI-P5511	ACI-P5510 ACI-P5511	ACI-5523
Nitrator 6 (N-6)	HRP-37-12899 HRP-37-12837	HRP-37-12837 HRP-37-12888	HRP-37-12883	HRP-37-13148
Nitrator 8 (N-8)	ACI-P5510 ACI-P5515	ACI-P5510 ACI-P5511	ACI-P5510 ACI-P5511	ACI-5523
Sellite Washer	HRP-37-12900	HRP-37-12928 HRP-37-12929	HRP-37-12900	HRP-37-12930
Acid Washer	HRP-37-12867	HRP-37-12921 HRP-37-12922 HRP-37-12424	HRP-37-12867	HRP-37-12925
Separator 6		HRP-37-12906		

HRP signifies drawings for the old Radford AAP continuous TNT manufacturing facility.

ACI refers to the new continuous TNT process utilizing dynamic separators at Volunteer AAP.

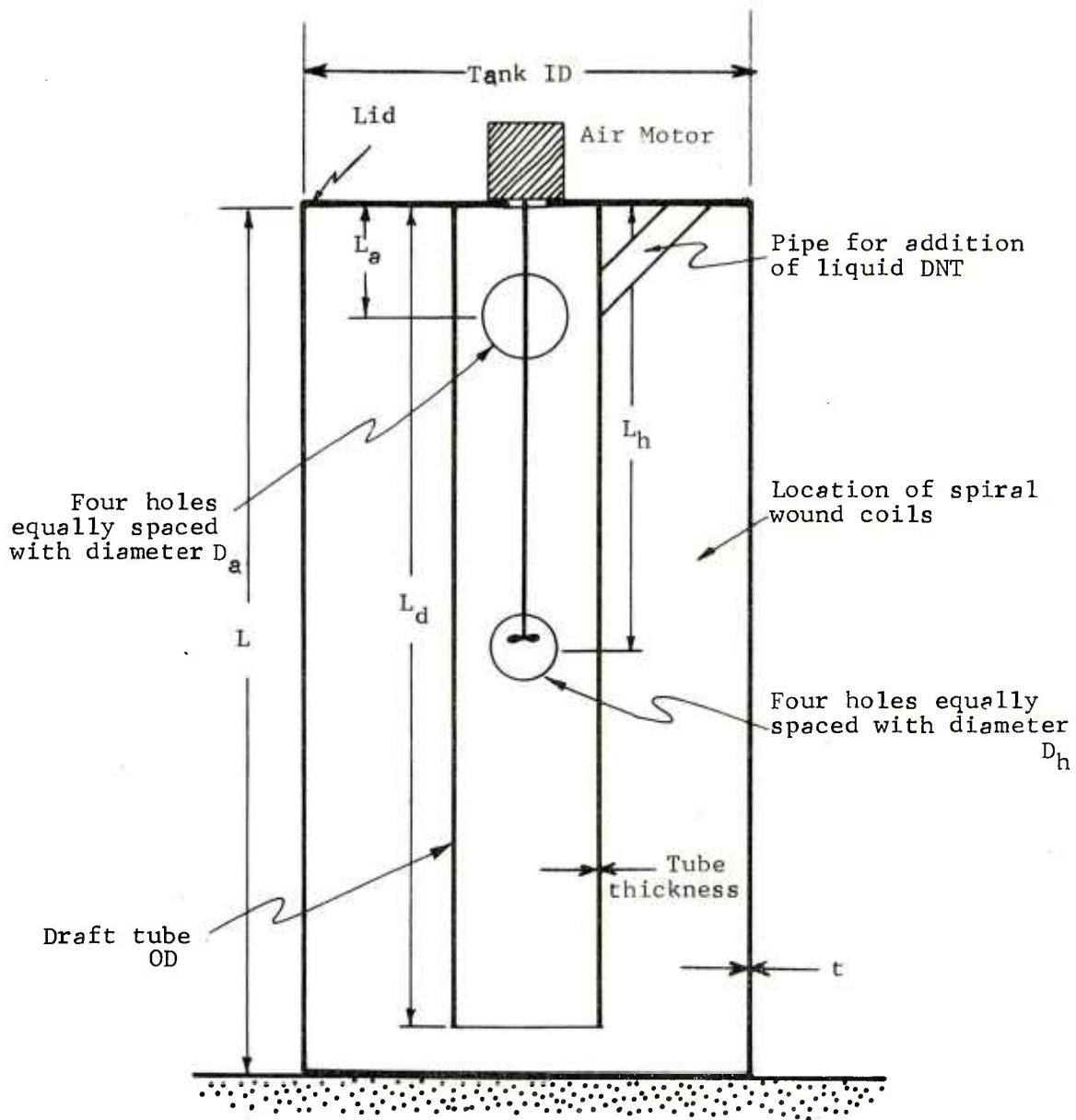


Fig 4 Reactor tank assembly (22.7 kg)

Table 6
Nitrobody reactor design scaled dimensions; 22.7 kg (50 lb)
(reference figure 4)

Reactor type	I. D. cm (inch)		L cm (inch)		Wall thickness cm (inch)		Material	Impeller diameter cm (inch)	Shaft length cm (inch)			
	3A	37.47 (12.25)	31.11 (12.25)	66.04 (26.00)	78.74 (31.00)	0.188 (0.074)		6.35 (2.50)	30.98 (12.00)			
Nitration 4	37.47 (14.75)	31.11 (12.25)	76.20 (30.00)	0.188 (0.074)	0.226 (0.089)	0.188 (0.074)	Carbon Steel	6.35 (2.50)	73.66 (29.00)			
Nitration 6	37.47 (14.75)	30.48 (12.00)	78.74 (31.00)	0.226 (0.089)	0.226 (0.089)	0.188 (0.074)	Carbon Steel	6.35 (2.50)	30.98 (12.00)			
Nitration 8	37.47 (14.75)	30.48 (12.00)	60.69 (24.00)	0.188 (0.074)	0.188 (0.074)	0.188 (0.074)	Carbon Steel	6.35 (2.50)	73.66 (29.00)			
Sellite washer								6.35 (2.50)	38.10 (15.00)			
Draught tube	L _d cm (inch)		L _a cm (inch)		L _h cm (inch)		D _a cm (inch)		D _h cm (inch)		Tube O.D. cm (inch)	Tube thickness cm (inch)
	62.23 (24.50)	9.84 (3.88)	31.75 (12.50)	4 holes: 6.03 (2-3/8)	31.75 (12.50)	4 holes: 6.03 (2-3/8)	4 holes: 6.03 (2-3/8)	4 holes: 6.03 (2-3/8)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	10.16 (4.00)	0.159 (0.063)
Nitration 4	74.61 (29.38)	9.20 (3.63)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	3.81 (1.50)	12.06 (4.75)	0.340 (0.134)	
Nitration 6	74.61 (29.38)	9.20 (3.63)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	3.81 (1.50)	12.06 (4.75)	0.340 (0.134)	
Nitration 8	74.61 (29.38)	9.20 (3.63)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	17.78 (7.00)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	4 holes: 4.13 (1-5/8)	3.81 (1.50)	12.06 (4.75)	0.340 (0.134)	
Sellite washer	45.75 (18.00)	4.29 (1.69)	11.43 (4.50)	4 holes: 4.76 (1-7/8)	11.43 (4.50)	4 holes: 4.76 (1-7/8)	2 holes: 4.76 (1-7/8)	2 holes: 4.76 (1-7/8)	3.32 (1.31)	3.33 (5.25)	0.318 (0.125)	
Material: Carbon Steel												
Cover	D cm (inch)		Thickness cm (inch)		Hole diameter cm (inch)		Material		Material			
	31.43 (12.38)	0.188 (0.074)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	Carbon Steel	Carbon Steel				
Nitration 4	37.94 (14.94)	0.226 (0.089)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	Carbon Steel	Carbon Steel				
Nitration 6	37.94 (14.94)	0.188 (0.074)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	Carbon Steel	Carbon Steel				
Nitration 8	37.94 (14.94)	0.226 (0.089)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	Carbon Steel	Carbon Steel				
Sellite washer	31.27 (12.31)	0.188 (0.074)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	4 holes: 0.381 (1.50)	Carbon Steel	Carbon Steel				

2.2.1.2 The Cover and Draft Tube Assembly

The cover and draft tube were welded together as a single unit. The full-scale draft tube was simplified in each case prior to applying the appropriate linear scaling factor. For example, the actual system had a series of slotted holes near the top of the draft tube and several holes at the impeller height of the tube. In the model, the flow area of the slotted holes was maintained but was represented by four circular holes evenly spaced around the tube. Similarly, four circular holes were drilled at the impeller level to represent the openings in the real system. A pipe was welded at about a 45 deg angle between the cover and draft tube as shown in figure 4. This pipe connected to the DNT drop tank and routed DNT into the draft tube during tests involving a batch nitration reaction.

2.2.1.3 Agitator System

In the small-scale tests, mixing was accomplished by using pneumatic motors. The agitation system was purchased as a unit including an air motor, shaft, and propeller as shown in figure 5. The shaft lengths were modified to reflect the proper scaled dimensions for each test requiring an agitator. Table 6 shows the different shaft lengths for the cylindrical configurations tested and table 7 gives shaft lengths for each box-shaped system tested. Prior to the tests, the motor was calculated to determine rpm versus air pressure with the impeller immersed in the test liquid. The motor was fastened to the cover and airpowered by using a compressor and storage tank as shown in figure 6. To record mixer rpm, a small magnet was positioned on the agitator shaft with a magnetic pickup located nearby on the cover. The rpm was scaled from the actual system so that the impeller tip speed was maintained constant. Table 8 is a list of the scaled rpm required for each test series. This produced approximately the same mixing action as existed in the full-scale systems.

The expendable pneumatic motor concept was chosen as the power system because of safety, and economic considerations. The pneumatic system was a simple design with few moving parts, therefore, the probability of malfunction was minimal. In contrast, the alternative was to design a permanent drive motor system with a variety of pulley sheaves to indirectly link the stirring rod and drive system. The permanent drive motor was to be buried underground in a protective enclosure. Capital and design costs for this concept were relatively high when compared to the expendable pneumatic motor concept.

Table 7
Nitrobody component design for box-shaped systems, scaled dimensions; 22.7 kg (50 lb)

<u>Reactor type</u>	<u>Component</u>	<u>Reference figure</u>	<u>Dimensions</u>			
			<u>L x W</u>	<u>H</u>	<u>t</u>	
Acid Washer (Carbon Steel)	Vessel	fig 9	27.94 x 27.94 (11.00 x 11.00)	63.60 (25.00)	0.236 (0.093)	
Draft tube		fig 9	<u>L_d</u>	<u>L_a</u>	<u>D_a</u>	<u>Tube ID</u>
Cover		fig 9	17.58 (18.75)	11.11 (4.38)	4.76 (1.88)	17.58 (6.92)
Impeller		fig 9	<u>L x W</u>	<u>t</u>	<u>Hole diameter</u>	<u>Hole diameter</u>
Separator (Carbon Steel)	Vessel	fig 8	<u>L x W x H</u>	<u>t</u>		

* Parenthesized dimensions in inches, nonparenthesized in centimeters.

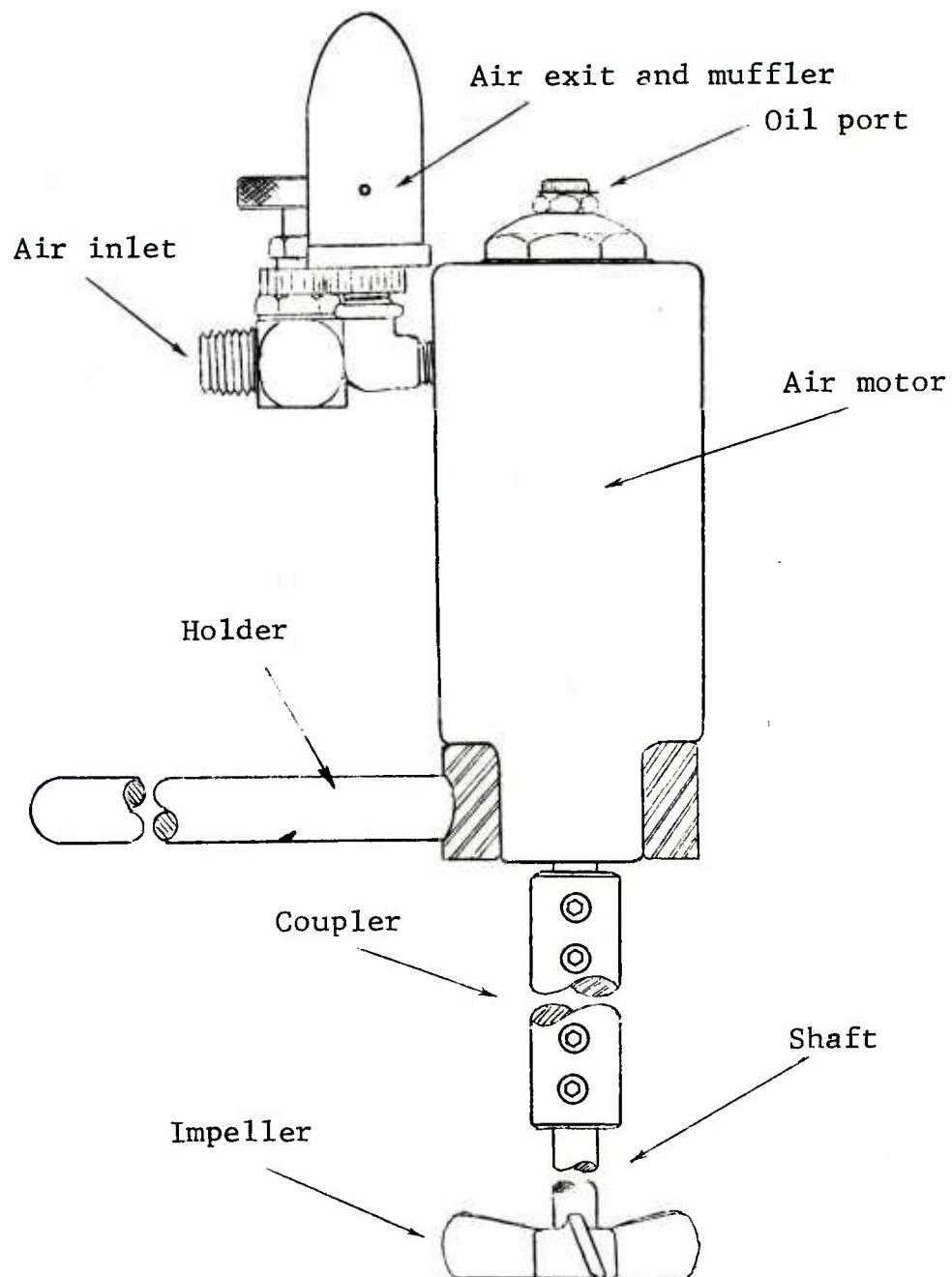


Fig 5 Agitator assembly

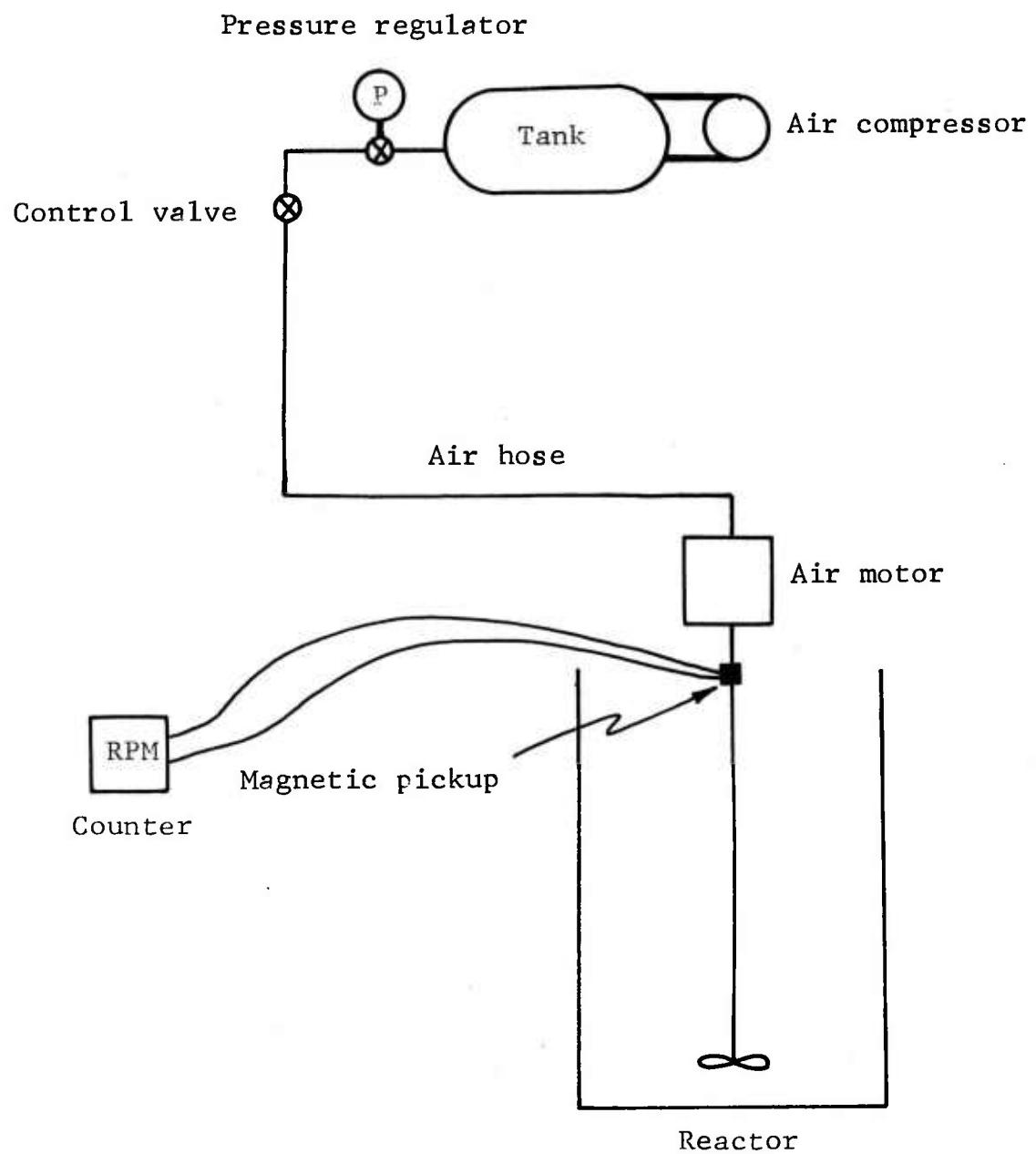


Fig 6 Power system for mixer

Table 8
Scaled rpm for small-scale tests

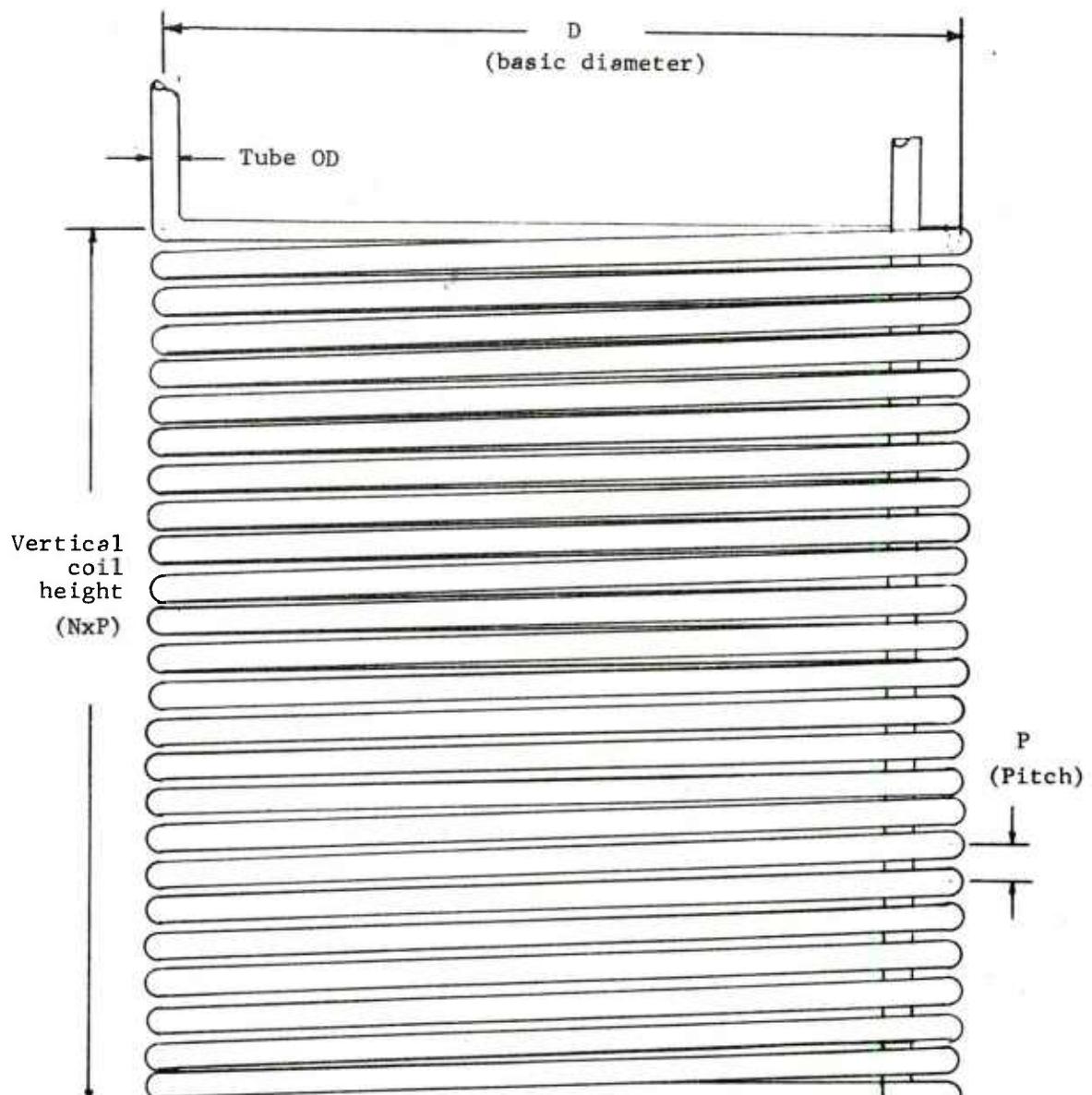
Test series	Model component	Scaled agitator	Actual full-scale
		rpm	rpm*
1	Old nitrator 3A	1710	450
2	Old nitrator 6	1710	450
3	Old separator 6	not applicable	not applicable
4	Acid wash tank	980	350
5	Sellite wash tank	1860	375
6	New nitrator 4	2318	450
7	New nitrator 5	2318	450
8	New nitrator 8	2318	450

* reference 7

2.2.1.4 Heating/Cooling Coil Configurations

In the initial stages of design, two mock coil configurations were investigated. One alternative was to use a vertical orientation of the tubing surrounding the draft tube. A series of 180 deg hairpin turns would be necessary to allow for direction change of the coil. In this case the important aspects of internal geometry and confinement would not be sacrificed and the series of nested coils surrounding the draft tube assembly would maintain nearly the same packing as the full-scale spiral configuration. The second alternative was to scale down the spiral arrangement existing in the real system. Both cases were studied for cost reduction and ease of fabrication and assembly. The spiral coil configuration was selected because it is the best simulation of the actual system and easiest to fabricate.

The scaled heat transfer coils served two functions in the experiments. First, they simulated the actual system internal geometry and resultant confinement. Second, they were used to heat the liquid in the tank to above the melting point of TNT and to cool the chemical mixture during the nitration of DNT. A spiral coil is depicted in figure 7 and the mock coil dimensions are presented in table 9 for each component tested. The coils have been numbered in order radially outward from the draft tube for identification.



N = number of spiral turns

Fig 7 Active heating-cooling coil for reactor (22.7 kg)

Table 9

Nitrobody coil design scaled dimensions^a; 22.7 kg (50 lb)
(reference figure 7)

	Coil	D ^c cm (inch)	L m (ft)	N (turns)	Pitch (P) cm (inch)
Nitrorator 3A	1	12.38 (4.88)	10.91 (35.80)	30	1.35 (0.53)
	2	15.56 (6.13)	13.29 (43.60)	29	1.35 (0.53)
	3 ^b	19.37 (7.63)	15.67 (51.40)	27	1.59 (0.63)
	4	22.54 (8.88)	18.00 (59.06)	27	1.59 (0.63)
	5	26.35 (10.38)	20.35 (66.78)	26	1.59 (0.63)
	6 ^b	29.53 (11.63)	22.70 (74.50)	25	1.59 (0.63)
Total: 100.88 (331.00)					
Nitrorator 4	1	13.65 (5.38)	18.40 (60.40)	46	1.11 (0.44)
	2	16.19 (6.38)	22.36 (73.35)	46	1.11 (0.44)
	3 ^b	19.37 (7.63)	26.33 (86.40)	46	1.11 (0.44)
	4	22.54 (8.88)	30.37 (99.50)	45	1.11 (0.44)
	5	26.35 (10.38)	34.25 (112.36)	43	1.11 (0.44)
	6 ^b	29.53 (11.63)	38.21 (125.35)	43	1.11 (0.44)
Total: 169.77 (557.00)					
Nitrorator 8	1	13.65 (5.38)	8.08 (26.50)	21	2.22 (0.88)
	2	16.19 (6.38)	9.68 (31.75)	21	2.22 (0.88)
	3 ^b	19.37 (7.63)	11.28 (37.00)	20	2.54 (1.00)
	4	22.54 (8.88)	12.89 (42.30)	19	2.54 (1.00)
	5	26.35 (10.38)	14.48 (47.50)	18	2.70 (1.06)
	6 ^b	29.53 (11.63)	16.08 (52.75)	18	2.70 (1.06)
Total: 72.50 (238.00)					
Acid washer	1 ^b	16.19 (6.38)	7.92 (26.00)	17	2.06 (0.41)
Sellite washer	1 ^b	21.27 (8.38)	14.02 (46.00)	22	1.43 (0.56)
Separator	(no coils present in separator)				

^aTube diameter for all coils was 0.95 cm (3/8 inch) OD

^bDenotes active coils used as heat exchangers

^cCenter to center basic diameter of coil

Coils number 3 and 6 were active coils used for heating and cooling the liquid in the tank. The remaining four coils were inert with the ends crimped to prevent liquid from entering.

2.2.1.5 Separator and Acid Wash Tanks

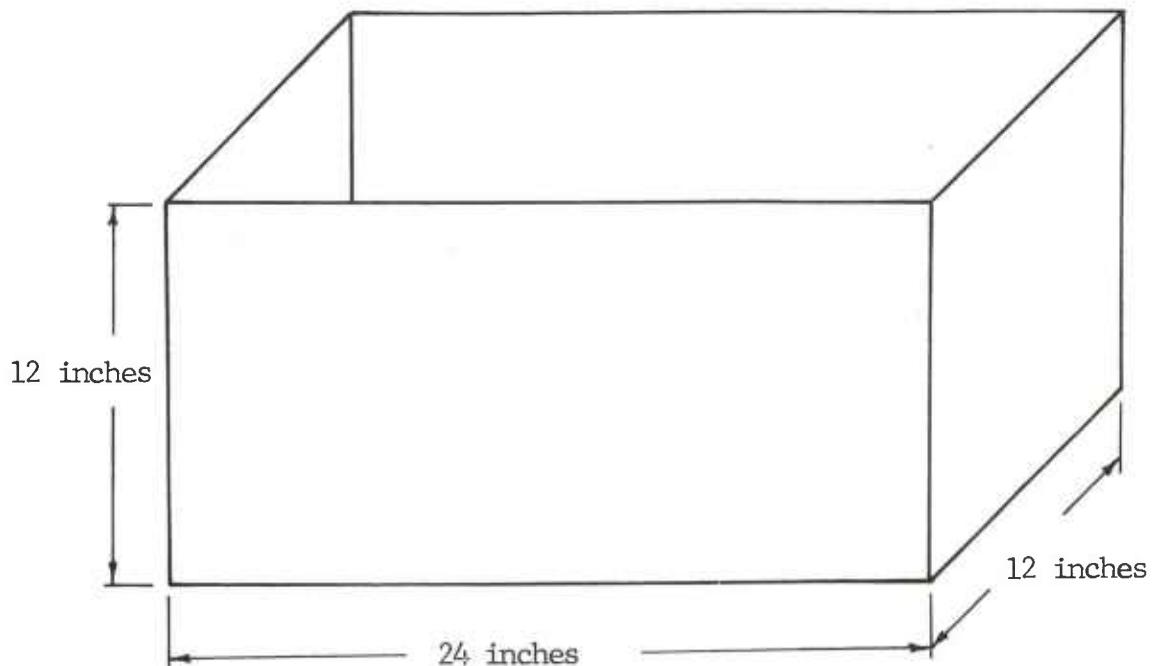
The separator and acid wash tank vessels represent the noncylindrical reactor configurations of the test program. A rectangular steel box was chosen to simulate the separator configuration. Figure 8 shows the scaled separator geometry. The acid wash tank simulation is illustrated in figure 9. Only the single mixing compartment at the TNT inlet was modeled. The model system consisted of a rectangular box and a cover assembly (including a draft tube). The heating jacket on the actual system draft tube was simulated by a heating coil in contact with the outer surface of the draft tube. Table 7 gives the significant dimensions for the separator vessel and acid wash tank compartment. See table 9 for the appropriate coil dimensions.

2.2.1.6 Booster Location

The booster arrangement for the agitated components is illustrated in figure 10. The test vessel sat on a wooden stand which was just high enough to fit a cylindrical C-4 explosive booster with a length to diameter ratio of 1. The flat upper face of the booster was in good contact with the thin steel tank bottom. Two tetryl pellets were used in each test to minimize the chance for a misfire.

For the separator tests, the cylindrical booster was placed on a wooden stand so that the flat surface of the cylinder would contact one end of the rectangular box at the height of the liquid TNT layer.

Several alternative booster arrangements were originally considered for the agitated systems before selecting the described arrangement. The first concept involved hanging the booster into the liquid from the tank cover. The booster and leads would be wrapped in a plastic bag for protection from the acid. This system was rejected because the booster would be moved around by the circulating liquid. The location of the booster would be uncertain; it could get caught in cooling coils, the draft tube or the stirring rod, depending on where it was hung; the bag might develop a leak and liquid could contaminate the booster either reacting with it or inerting the initiators. Another option was to drop the booster into the tank by means of a solenoid immediately before initiation. This option was considerably more complicated and less certain when compared with simply boostering from underneath the tank.



Wall thickness preferably 0.069 inch

Fig 8 Separator vessel

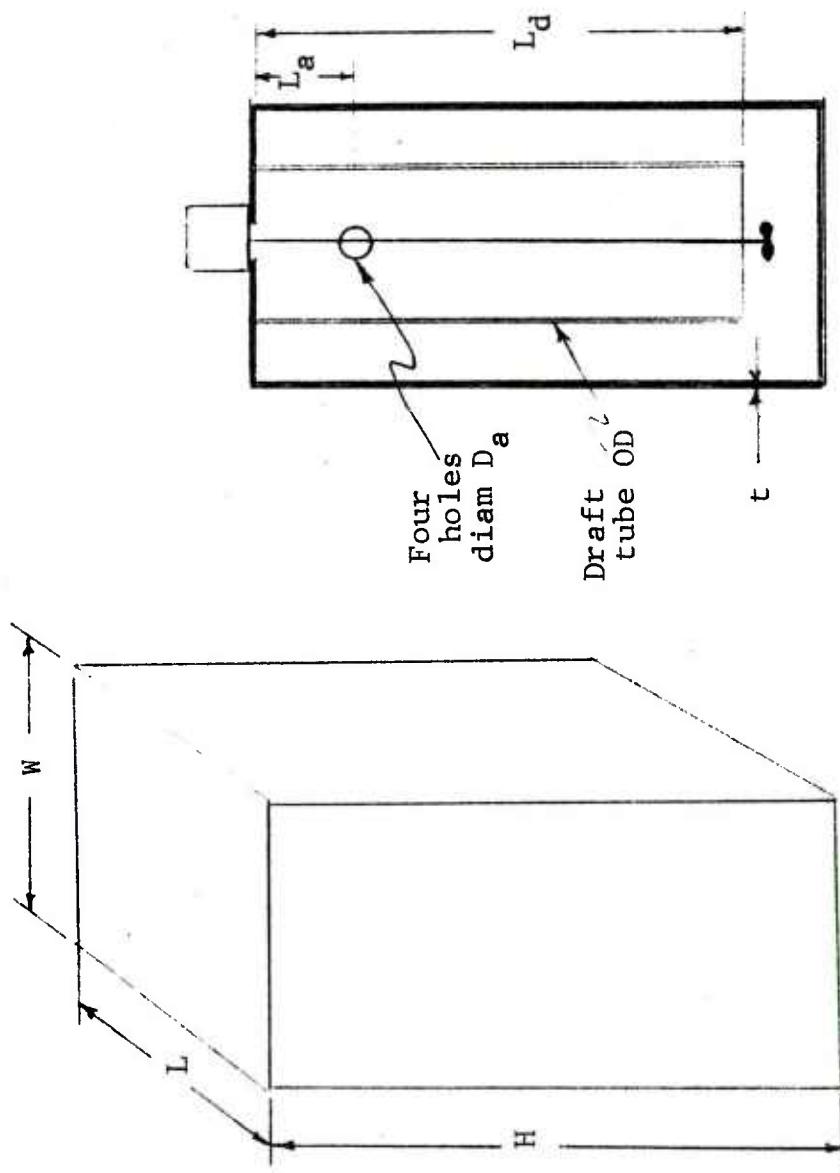


Fig 9 Acid washer configuration

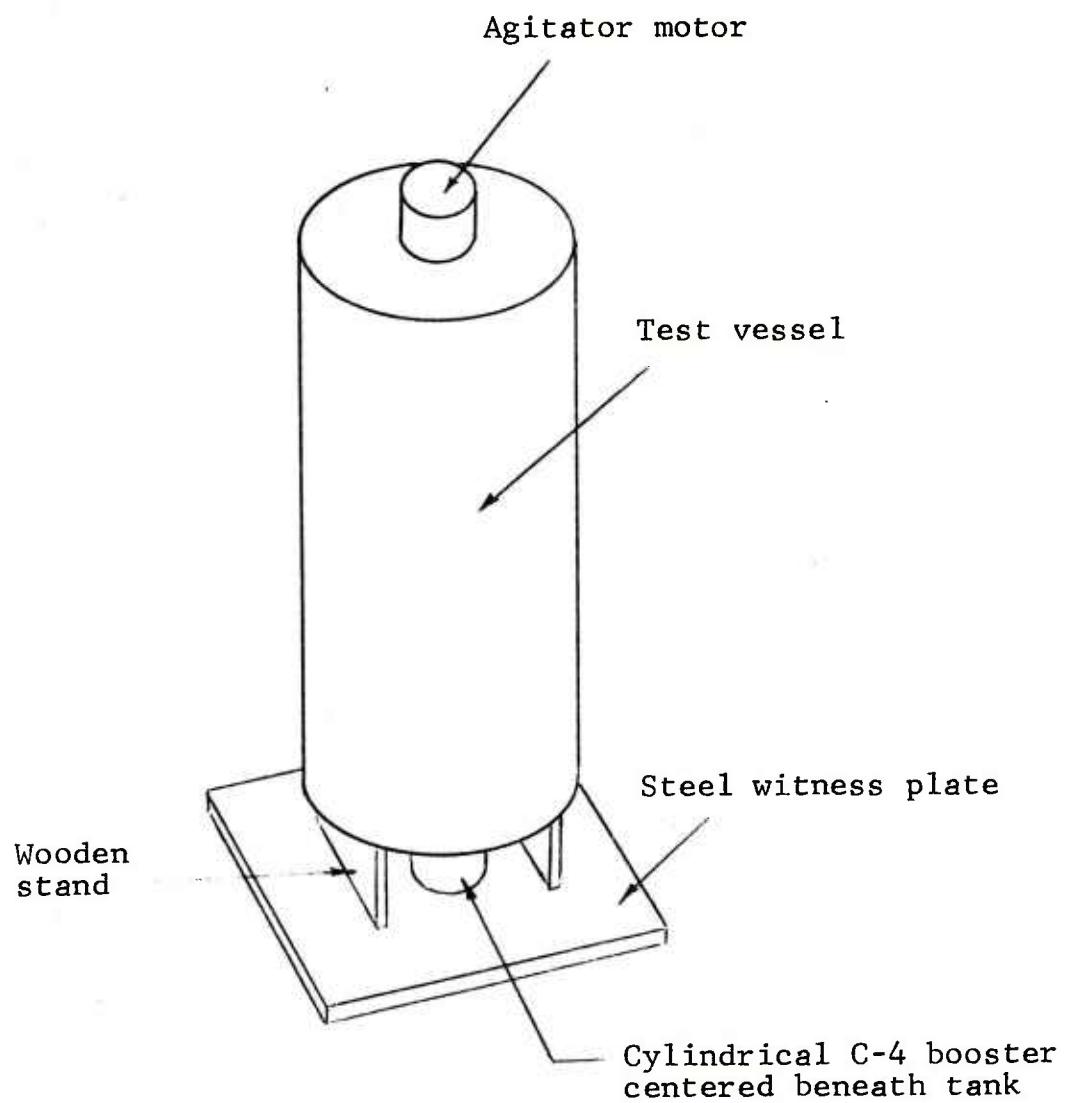


Fig 10 Booster underneath tank

2.2.2 Instrumentation

The instrumentation system used in the small-scale test series is described in this section. The rationale for transducer selection and the experimental procedures used in the test program are included. The diagnostic data consisted of: pressure-time measurements, pressure impulse-time measurements and detonation velocity measurements. Temperature measurements and agitator shaft speed measurements were used to monitor and control the pretest conditions.

The recording equipment was housed in a field trailer located about 137 m (450 ft) from the test area. The control equipment was located in a hardened bunker located about 76 m (250 ft) from the test area.

2.2.2.1 Pressure and Impulse Measurements

It is important to report IITRI procedures for obtaining the experimental data, but an in-depth description would be somewhat lengthy to present in the main body of this report. Accordingly, a detailed description of the instrumentation equipment, calibration method, and computational procedures is included in Appendixes A and B.

Pressure measurements were made at the designated stations on each of two gage lines. The gage lines were centered in two 23 m (75 ft) long by 3 m (10 ft) wide concrete slabs located at right angles to one another. The gage lines are designated the north line (N) and the east line (E). The pressure transducers were installed flush with the top surface of the concrete slab in steel plates. The steel plates cover a channel in which the transducer leads are laid. The transducers were electrically isolated from the steel plate and from each other by using insulated mounting adapters.

The pressure transducers were located in both gage lines at the same relative distance with respect to the center of the test area (i.e., intersection of the gage lines). Two types of pressure transducers were used; the piezoelectric type and the capacitive type. The positioning of the transducers by type was the same on both gage lines. Table 10 summarizes the transducer layout along each gage line.

Piezoelectric type transducers were used in positions where the pressure-time profile is characterized by high peak overpressure and short positive duration. The capacitance type transducers were used in the last four positions because high pressure resolution and DC response are desirable at these locations. Gage position 7N was added to

the north gage line for this test program. The transducer is mounted in a steel plate, 0.61 m (2 ft) by 0.61 m (2 ft) by 2.54 cm (1 inch) thick. The steel plate is staked to the ground by four pins, one at each corner.

Table 10
Transducer assignment

<u>Gage position</u>		<u>Transducer</u>	
		<u>Location</u>	<u>Type</u>
<u>m</u>	<u>(ft)</u>		
1N	1E	2.7 (8.8)	Piezoelectric
2N	2E	3.7 (12.0)	Piezoelectric
3N	3E	5.2 (17.0)	Piezoelectric
4N	4E	8.2 (27.0)	Capacitance
5N	5E	12.0 (39.4)	Capacitance
6N	6E	24.5 (80.5)	Capacitance
7N		43.0 (141.0)	Capacitance

The pressure-time functions were recorded on magnetic tape and reproduced on an oscillograph recorder. Similarly, the pressure signals were integrated, real time, and pressure impulse was recorded on magnetic tape and reproduced on an oscillograph recorder. The oscillograph printouts provide the means for assessing the blast wave characteristics as a function of scaled distance.

2.2.2.2 Detonation Velocity Measurements

From the outset of the experimental program, it was recognized that detonation velocity measurements for the TNT nitrobody tests presented a challenging instrumentation problem. To obtain this measurement, it was necessary for the gage system to survive in a hostile environment for an extended period of time prior to the test event. Harsh acid, at elevated temperature, and continuous agitation of the test material describes the environment in general terms. The acid is electrically conductive, thus presenting an implementation problem for using ionization probes.

The value of obtaining detonation velocity was apparent; however, development effort, including major modifications, was not considered to be within the scope and time frame of the program. Relatively minor modification of existing

systems was viewed as the acceptable approach. Accordingly, the established methods for obtaining detonation velocity were reviewed. The IITRI approach was to determine which of the measurement techniques used could be modified for use in this application. Also, to determine the modifications required and to assess the influence of the modifications on the measurements. Limiting the methods to those used by IITRI was not arbitrary because the system(s) selected had to be available in a timely manner. This, in turn, required that the equipment and operating procedure be readily available.

The measuring techniques used by IITRI on previous test programs include high-speed photography, ionization probes, fiber optics probes, and continuous velocity probes.

High-speed photography is a proven method for measuring the arrival time of the detonation front. The test item configuration necessary to implement this method conflicted with other program requirements and the method was not seriously considered.

Ionization probes are used routinely for obtaining time-displacement measurements in explosives. They are reliable, rugged, and easily used. The serious shortcoming for this application is that they cannot be used in an electrically conductive material.

Fiber optics probes can be used in conductive materials. Unfortunately, preliminary test showed that the plastic light guide could not tolerate the acid environment; however, the PVC sheathing would survive the acid environment.

Continuous velocity probes are usually made of thin walled aluminum tubing. The basic design could not be used because the aluminum tubing would not survive in the acid mixture.

The initial IITRI appraisal indicated that the fiber optics probe would be the logical choice. Modification of the existing system would require a glass bead protective covering over the exposed fibers. Similar systems use a lens system at the receiving end so it did not appear that the measurements would be unduly influenced by the protective glass cover. The ionization probes also require a glass bead cover over the exposed ends to provide electrical insulation. In this case, however, the glass must be broken by the detonation front before the ionization could be detected. This presented some uncertainty regarding the reliability of the measurement.

The continuous velocity probe appeared to be the least attractive choice. Coating the aluminum tubing with acid resistant material did not appear to be a reasonable approach because the probes are fragile and do not tolerate excessive handling. Changing the sheath material was considered but this appeared to be a significant modification at the time. However, this approach was eventually adopted as described in subsection 2.3.2.2.

The IITRI decision was to use the modified fiber optics system as the primary measuring system. Previous experience showed that this was a reliable and simple system to use. The equipment required to field this system was on hand and the experimental procedures were understood. Backup measurements were desirable because of no first hand experience in using the modified system in the test environment. Simulating the test conditions for evaluation and performance testing was not practical because the effort required for a valid simulation was roughly equivalent to fielding the test item.

Modified ionization probes were used as a backup system. The uncertainties regarding the influence of the modification were recognized but it was believed the method had potential that required consideration. This was a logical selection since the equipment and techniques were available and the modification was relatively simple. It should be noted that in theory, the modified version of the ionization probe is analogous to the continuous probe. Both systems require a structural failure (crushing) to generate a data signal. A notable exception is that the ionization probes produce signals at discrete locations while the continuous velocity probe system, as its name implies, provides a continuous time-displacement record.

Ionization Probes: The ionized gases at the detonation front are electrically conductive and the ionization probes are used to detect the arrival of the electrically conductive gases at the measuring stations. In its simplest form, the ionization probe consists of two conductors separated by an insulator, usually the explosive material. A conductive path is established between the conductors at the time-of-arrival of the detonation front.

Clearly, many methods could be used to sense the existence of the conductive path because it is simply a switch closure. The signal conditioning circuitry used here is a simple series circuit shown in figure 11(a). In the actual test, the individual circuits were cascaded and polarized so that signals from six probes were recorded on a single oscilloscope channel. The theory of operation is similar

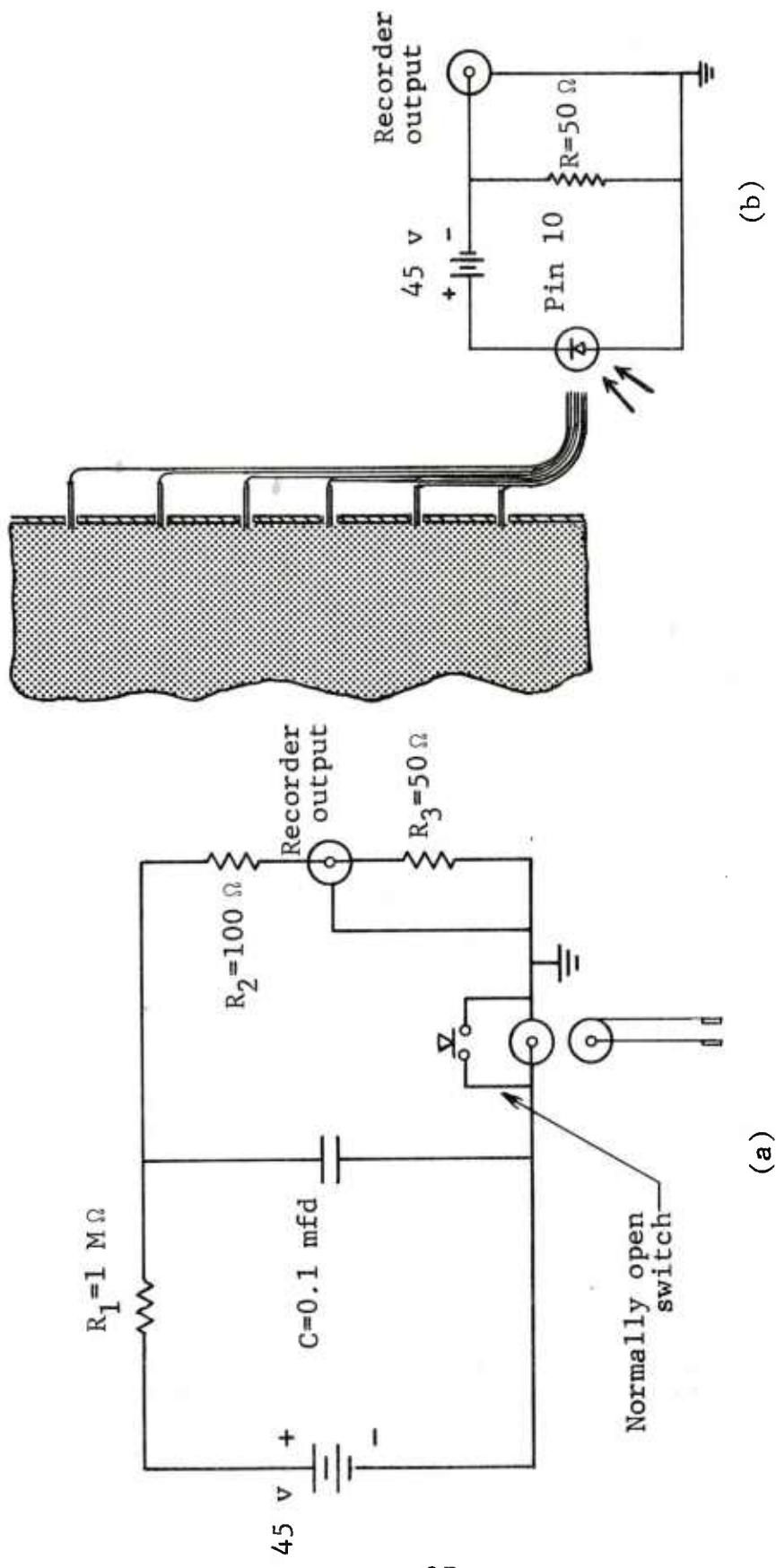


Fig 11 (a) Ionization probe signal conditioning circuitry and (b) fiber optics probe diagram

for the multi-probe unit and the single probe unit shown. Referring to figure 11(a) and noting the charge path for the capacitor, C , is through R_1 . The charge time is approximately $5R_1C = 0.5$ sec. The capacitor remains charged until ionization occurs and the discharge path is completed. The discharge path is through R_2 and R_3 , thus producing a discharge time of $5C(R_2 + R_3) = 75 \times 10^{-6}$ sec. The discharge cycle will produce a voltage rise across R of 7.5 volts. In summary, the arrival of the detonation front at the measuring station will produce a voltage pulse of 7.5 volts at the output of the unit. The pulse will decay to zero at an exponential rate in 75×10^{-6} sec. The occurrence of additional pulses is effectively "held off" for a time determined by the resistance of the charge path.

For the present application, glass insulators were placed over the conductors to insulate the probes from the conductive acid. Accordingly, the measure may represent the breaking of the glass insulators due to the arrival of the shock front.

Fiber Optics Probe: The basic operating principle of the fiber optics probe is: The intense light generated at the detonation front in an explosive is conducted to the sensitive element of a photodiode by means of optical fiber. An electrical pulse is produced by the photodiode when the detonation front reaches the fiber end in contact with the explosive. The electrical pulse is displayed on a single sweep oscilloscope.

The fiber optics probe has been shown to be a reliable technique for the measurement of the arrival of a detonation front. Measurements can be made in electrically conductive materials. It is not necessary to bring voltage near the explosive during the measurement which makes this method attractive.

The IITRI fiber optics probe was developed with the aid of work reported by Leslie (reference 8). The schematic diagrams of the IITRI system is shown in figure 11(b). Crofon plastic light guides are positioned at locations within the explosive material. Sixteen strands of 10 mil plastic fiber enclosed in PVC sheath form the Crofon light guide. The light guides are bundled and the open ends were positioned near the active area of a PIN-10D photodiode. The active area of the photodiode is 1.0 cm^2 (0.16 inch^2) and the unit is operated in the photoconductive mode.

As previously mentioned, a glass bead was cemented over the tip of the light guide to protect the plastic fiber from the acid in the present application. The glass bead was held in place with epoxy cement.

Evaluation: The modified probes were tested using conventional explosives to verify the operation of the system. Both probes worked well as anticipated. This confirmation is a necessary step before using the probes in the nitrating acid mixtures.

During the initial testing in the acid environment, the quality of the data was not good; particularly with the fiber optics probes. The test work continued and different scale sensitivities and probe orientations were tried. Finally, after the fifth test, the test program was stopped to investigate the problem related to the fiber optics probes. A faulty circuit component was discovered and replaced and the test series continued. The quality of the data improved but not to an acceptable level. Our decision was to continuously work to improve the data without further interrupting the scheduled testing.

2.2.2.3 Temperature Measurements

Temperature measurements were made in the melt kettle and in the reactor tank. Cromel-alumel thermocouple probes were inserted through the side wall of the reactor tank near the bottom and at the middle of the tank. Epoxy was used to hold the probes in place and to provide a seal. The thermocouple probes were 15 cm x 0.16 cm diameter (5 inch x 1/16 inch diameter).

The reference junction was located near the test area and the data signals were conducted via shielded copper cable to the recording station. The data was recorded on a multipoint strip chart recorder. Thermocouple reference tables were used to convert the voltage readings to temperature readings.

The temperature measurements were used to determine the pretest conditions of the test item and to provide information for operating the heating/cooling system. The system did not have the required response characteristics for monitoring temperature data during the tests.

2.2.2.4 Agitator Shaft Speed Measurements

The agitator shaft speed was monitored by using a permanent magnet (Alnico V) and a miniature magnet reed switch. The permanent magnet was bonded to the shaft where it enters the reactor tank. The magnetic reed switch was mounted on the agitator motor holder (see figure 5). The spring between the magnet and the reed switch was about 0.48 cm (3/16 inch), thus providing a switch closure for about 60 deg

of shaft revolution. Actuating time for the reed switch is less than 1 msec.

The switch closure was used to shunt a load resistor in a simple current limited voltage supply. The output signal was a series of pulses whose repetition rate was proportional to shaft speed. The shaft speed data was displayed on an electronic counter.

2.2.3 Support Equipment and Test Site

The described mock TNT process components required several support systems to complete the tests. A heating/cooling system was required to supply hot water to the active coils inside the test vessels during the heating of the acid or wash solution and to supply cold water to the active coils to cool exothermic reactions, such as the nitration of DNT. A melt system was required to provide liquid TNT and DNT for the tests. Finally, the site had to be instrumented with two mutually perpendicular pressure transducer lines for determining TNT equivalencies. Protective structures to house equipment and personnel had to be present at the test site.

2.2.3.1 Heating/Cooling System

The heating/cooling system for the experiments is diagrammed in figure 12. Water was heated in the hot water reservoir using a propane gas burner. During the heating cycle, a 746 watts (1 hp) centrifugal pump circulated water in the loop shown through the active coils in the test vessel. When cooling was required the centrifugal pump would be turned off and all solenoid valves energized simultaneously. Cold tap water was forced through the active coils and then drained onto the ground.

2.2.3.2 Explosive Melt-Pour System

DNT and/or TNT explosive flakes were weighed and then manually heated in a large melt kettle heat exchanger until liquid. Once the melt cycle was completed, liquid TNT was manually added to the acid in the test vessel and liquid DNT was poured into the DNT remote feed tank in the field.

The DNT remote feed tank is shown in figure 13. This 19 liter (5 gallon) container was located above the reactor vessel and connected to the reactor through a pipe extension protruding at about a 45 deg angle from the cover plate.

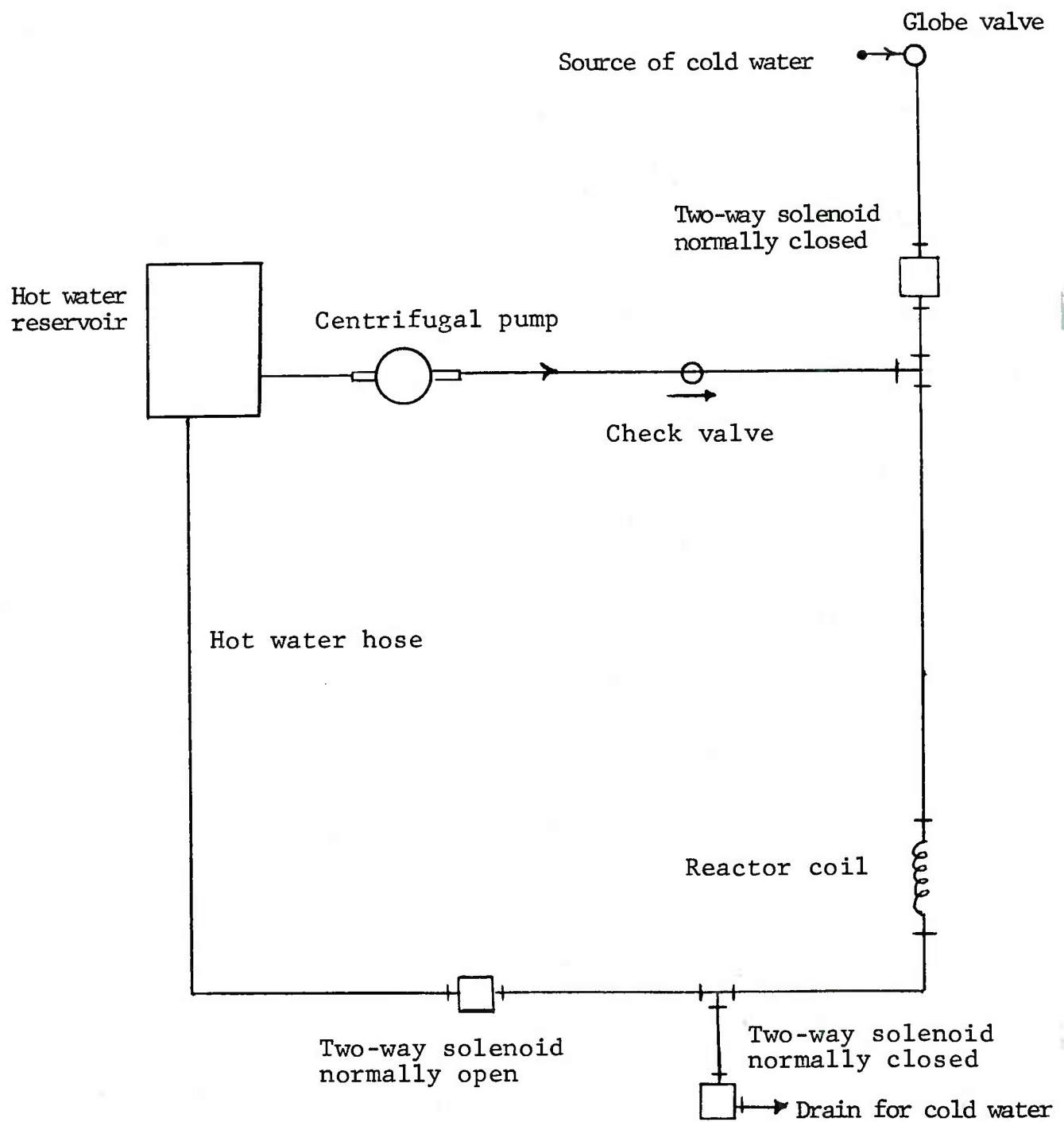


Fig 12 Reactor heating-cooling system

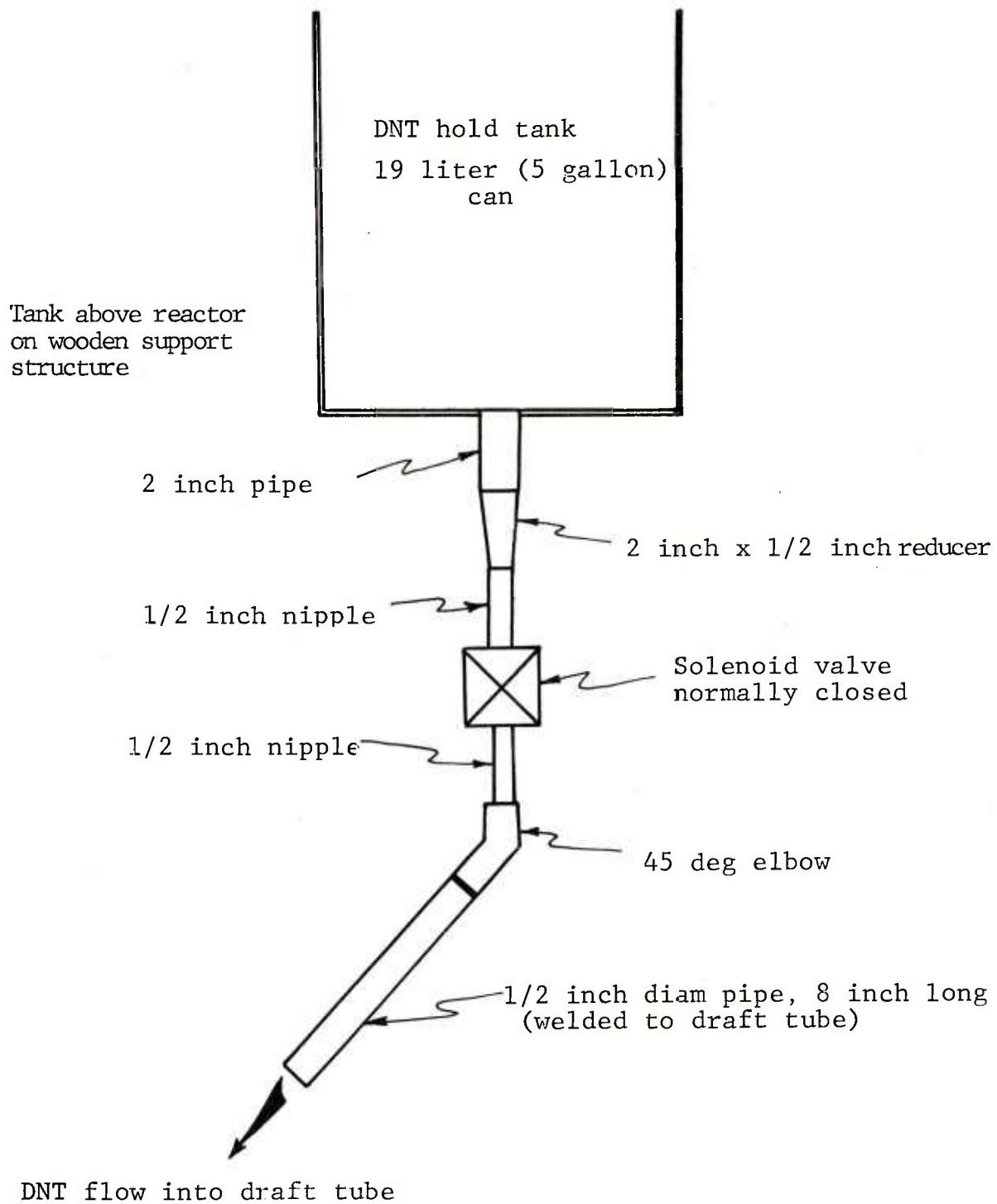


Fig 13 DNT remote feed system

Two heating tapes surrounded the DNT holding tank to maintain the DNT contents above its freezing temperature during the period just prior to detonation. A heating tape was wrapped around the pipe extension feed line to prevent freeze-up during the drop cycle. A normally closed solenoid valve was positioned in the pipeline to act as the gating mechanism. When the solenoid valve was activated, the DNT would flow through the 45 deg angle pipe through the cover and into the draft tube.

2.2.3.3 Test Area

The 22.7 kg (50 lb) scale tests were conducted at the IITRI Explosives Research Laboratory near LaPorte, Indiana. A schematic diagram of the physical arrangement of the test area is shown in figure 14. It consists of two concrete slabs 22.9 m (75 ft) long by 3.05 m (10 ft) wide on which 12 pressure transducers were installed. The pressure transducers were mounted flush with the top surface of the concrete slab in mechanically isolated steel plates. One additional pressure gage was mounted in a steel plate and positioned on the far north leg (see figure 13). The steel plate was securely anchored to the ground. The test component was positioned at ground zero as indicated on figure 14. The test charge for each configuration was placed on a 45.72 cm (18 inch) by 45.72 cm (18 inch) by 2.54 cm (1 inch) thick 1020 carbon steel witness plate. For the agitated vessel configurations, a wooden stand was positioned between the reactor and witness plate to support the structure and allow clearance for placement of the booster charge (see section 2.2.6).

Pressure and impulse measurements were made 2.67 m (8.75 ft) to 42.96 m (140.9 ft) from the charge. Scaled diameters ranged from $0.90 \text{ m/kg}^{1/3}$ ($2.26 \text{ ft/lb}^{1/3}$) to $14.6 \text{ m/kg}^{1/3}$ ($36.8 \text{ ft/lb}^{1/3}$). Table 11 gives the exact gage locations used during this test program.

Table 11
Pressure transducer gage locations
22.7 kg (50 lb) nitrobody reactor system

North Gage	Distance m (ft)	East Gage	Distance m (ft)
1N	2.69 (8.83)	1E	2.67 (8.75)
2N	3.66 (12.00)	2E	3.70 (12.13)
3N	5.18 (17.00)	3E	5.16 (16.92)
4N	8.38 (27.50)	4E	8.22 (26.96)
5N	11.98 (39.20)	5E	12.03 (39.48)
6N	24.61 (80.75)	6E	24.59 (80.67)
7N	42.96 (140.90)	--	

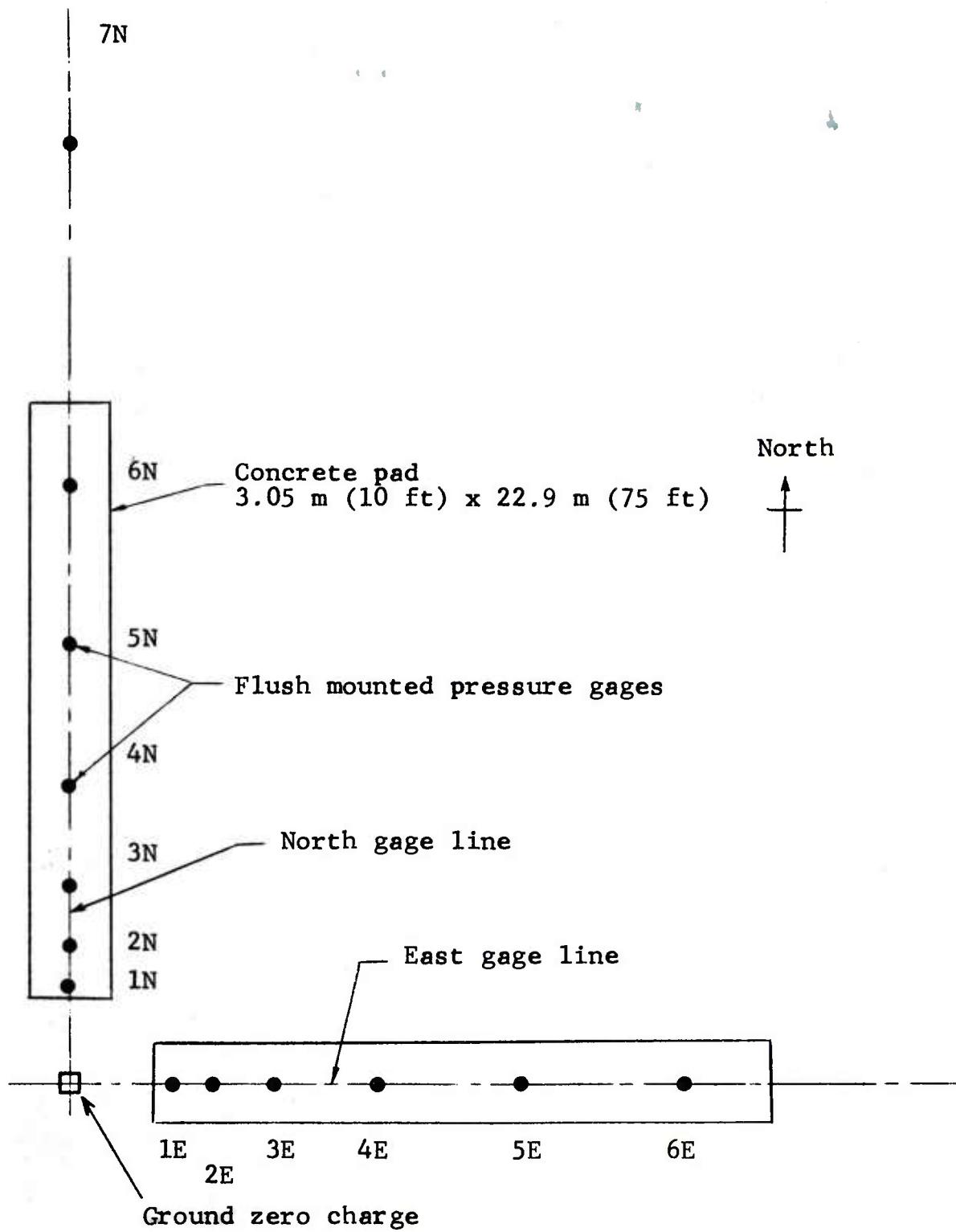


Fig 14 IITRI test area (not drawn to scale)

Support equipment including a hot water reservoir, pumps and solenoid components were positioned behind a rivetment approximately 53 m (175 ft) from ground zero in line with the east gage line. In the same proximity at 60.96 m (200 ft) from ground zero an existing steel building was used to house the control equipment for the tests. The temperature recorder, the heating tape variac the DNT solenoid switch, the air compressor system and pressure reducing station, the propane gas cylinders and firing line switch were located at the steel building.

2.3 Design of Large-Scale 90.8 kg (200 lb) Experiments

Eight large-scale tests were to be completed at the NSTL facility near Bay Saint Louis, Mississippi. Due to operational and weather problems, only one of those tests was successfully completed. That test was from the new nitrator 8 series and did not detonate. Considerable effort went into planning the tests and designing the system. The large-scale tests may be worthwhile completing in order to verify scaling. It is possible that these tests or similar experiments for another chemical process will be required. So that such tests can be completed with a minimum of effort at another facility in the future, the complete system design is described in this section.

2.3.1 Design of Mock TNT Process Components

The mock nitration reactors to be tested at NSTL consisted of a cylindrical steel tank, a cover and draft tube assembly, an electric agitator system, and heat transfer coils. The reactor assembly is pictured in figure 15 and dimensions for the three reactors to be tested are given in table 12.

A large DC 560 watt (3/4 hp) electric motor was centered on the cover to rotate the agitator shaft. To ventilate the motor to prevent deterioration due to acid fumes, the motor was elevated slightly above the cover on a wooden stand. A three-bladed propeller with a 10.16 cm (4 inch) diameter and a 45 deg pitch was at the bottom of the agitator shaft. A counterclockwise rotation of the propeller produced a downward flow of the liquid.

The heat transfer coils used in the large-scale model reactors were scaled closely from the full-scale system. No inaccuracies had to be introduced due to using a single coil diameter for all the systems, such as was the case for the small-scale tests. Coils were procured from a vendor and accurate diameters could be specified. Each reactor contained six concentric spiral wound coils located between the draft

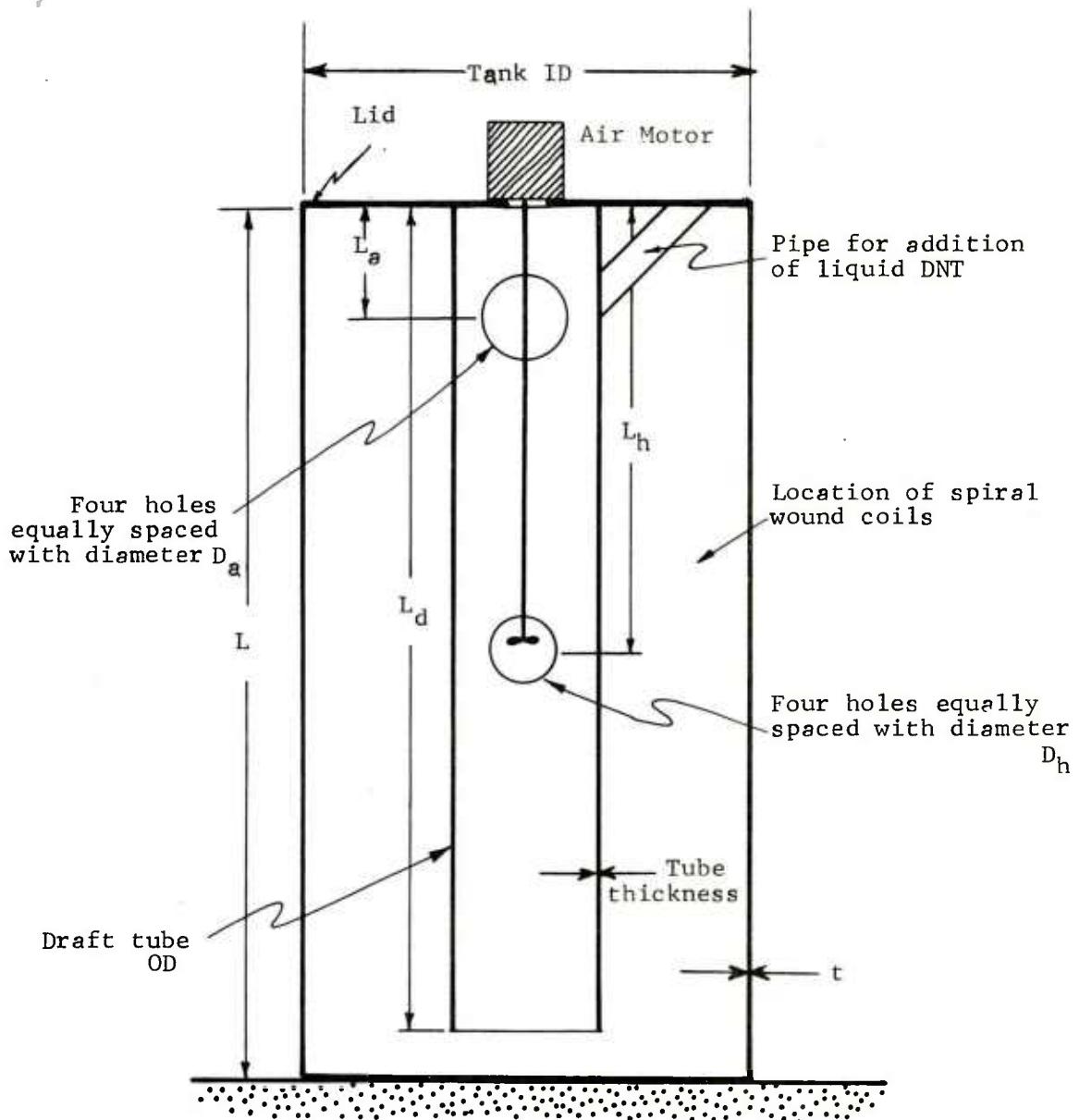


Fig 15 Reactor tank assembly (90.8 kg)

Table 12
Nitrobody reactor design scaled dimensions; 90.8 kg (200 lb)
(reference figure 15)

Reactor Type	I.D. cm (inch)		L cm (inch)	Wall thickness cm (inch)	Material	Impeller diameter cm (inch)		Shaft length cm (inch)
Nitrat or 4	59.53	(23.44)	125.73	(49.59)	0.340 (0.134)	Carbon steel	10.16 (4.00)	121.92 (48.00)
Nitrat or 6	51.28	(20.18)	108.88	(42.87)	0.302 (0.119)	Carbon steel	10.16 (4.00)	53.34 (21.00)
Nitrat or 8	58.42	(23.00)	122.55	(48.25)	0.340 (0.134)	Carbon steel	10.16 (4.00)	119.38 (47.00)
Contain er								
L _d cm (inch)		L _a cm (inch)		L _b cm (inch)		D _a cm (inch)	D _b cm (inch)	Tube O.D. cm (inch)
Nitrat or 4	119.07	(46.88)	18.75	(7.38)	60.96	(24.00)	11.43 (4.50)	9.22 (3.63)
Nitrat or 6	102.72	(40.44)	16.36	(6.44)	52.40	(20.63)	9.86 (3.88)	7.95 (3.13)
Nitrat or 8	116.20	(45.75)	18.42	(7.25)	59.39	(23.38)	11.13 (4.38)	8.89 (3.50)
Draft Tube								
D cm (inch)		Thickness cm (inch)		Hole diameter cm (inch)		Material		
Nitrat or 4	60.33	(23.75)	0.340	(0.134)	5.08	(2.00)	Carbon steel	
Nitrat or 6	51.92	(20.44)	0.340	(0.134)	5.08	(2.00)	Carbon steel	
Nitrat or 8	59.21	(23.31)	0.340	(0.134)	5.08	(2.00)	Carbon steel	
Lid-Cover								

tube and the outer tank wall. The coils were fabricated from seamless carbon steel tubing in accordance with SAE J526B. Figure 16 and table 13 provide the coil design specifications for the large-scale reactor tests.

The reactor assembly was positioned on a wooden stand so that a C-4 explosive booster could be placed beneath the tank in contact with the tank bottom. The booster was cylindrical in shape with an approximate length to diameter ratio of 1. Shims were used to wedge the flat surface of the booster cylinder tightly against the reactor surface. A variety of molds were provided so that booster weights of 9.08 kg (20 lb -- 10%⁵), 13.62 kg (30 lb -- 15%⁵) and 18.16 kg (40 lb -- 20%⁵) could be used in the test program. J-2 blasting caps with independent firing lines were imbedded in the booster charge to ensure fault-free initiation.

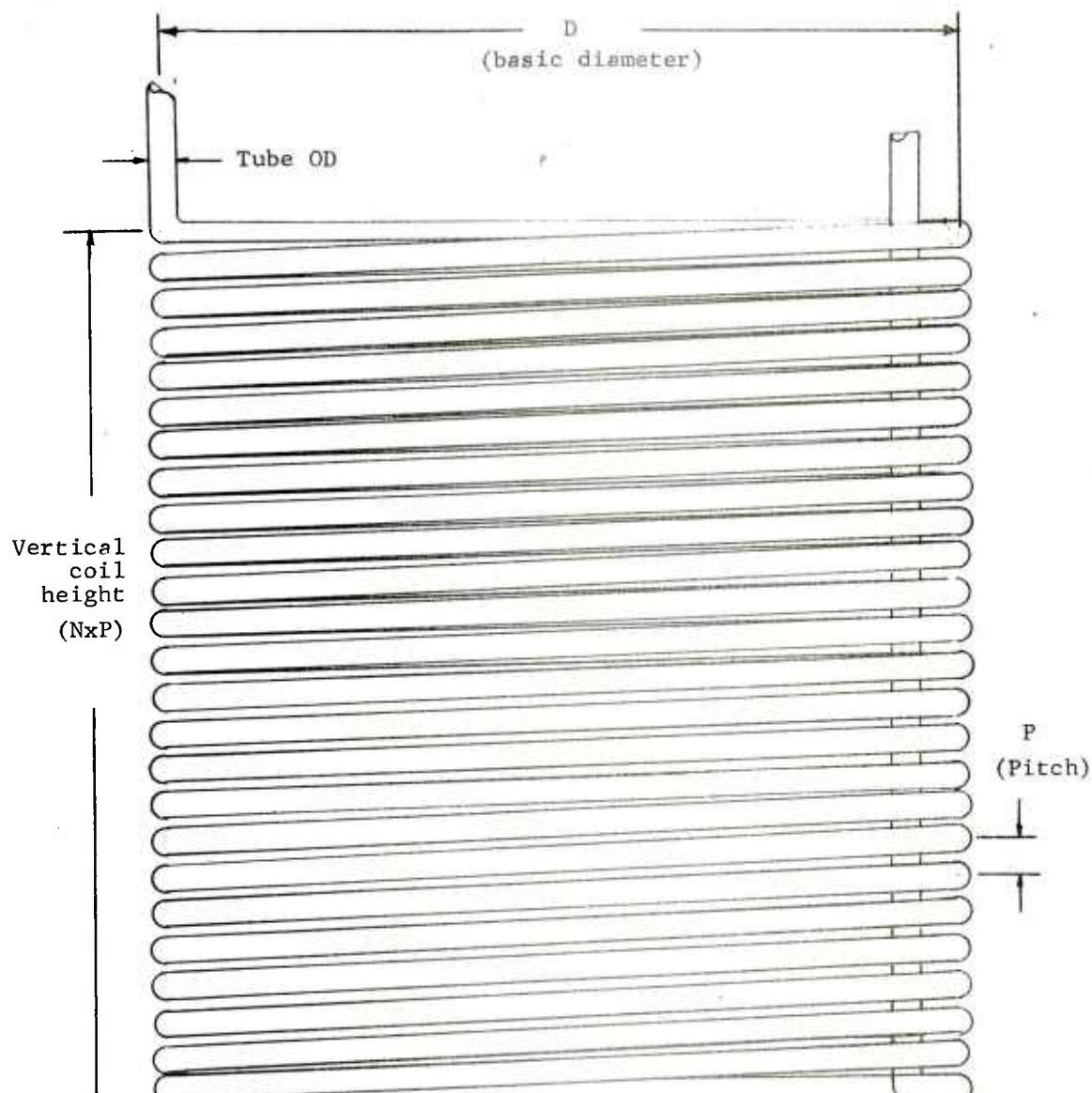
The wooden stand and booster sat on a 0.91 m (3 ft) x 0.91 m (3 ft) x 2.54 cm (1 inch) steel whitness plate. Figure 17 shows the insulated reactor assembly in the field. The heat transfer coil leads, manifolds and hose connections can be seen in the photograph. Figure 18 shows the insulated reactor positioned under the TNT/DNT melt sled. The sled carried two steam kettles and a steam generator system. TNT and/or DNT would be melted in the kettles and allowed to flow into the reactor by opening solenoid valves at predetermined times prior to initiation.

2.3.2 Instrumentation

The diagnostic data recorded in the NSTL tests consisted of pressure-time measurements along the gage lines and detonation velocity measurements inside the reactor draft tube. Pretest verification and control data consisted of temperature measurements in the reactor tank, the melt/mix kettles, and in the heating/cooling system. The agitator shaft speed was displayed on an electronic counter. Additionally, closed circuit television was used to monitor the test area and to verify certain test functions.

A dugout was used to house the field signal conditioning equipment. The dugout was a shallow hole dug in the ground between the gage lines and located about 9.1 m (30 ft) from ground zero. The dugout was lined with plastic to protect against moisture and the everpresent seepage.

⁵ Percent of nitrobody weight.



N = number of spiral turns

Fig 16 Active heating-cooling coil for reactor (90.8 kg)

Table 13

Nitrobody coil design scaled dimensions;^{a,b} 90.8 kg (200 lb)
(reference figure 16)

Reactor Type	Coil	D ^c cm (inch)	L m (ft)	Pitch (P) cm (inch)	Tube O.D. cm (inch)
Nitrator 4	N4-1	26.67 (10.50)	21.65 (71.00)	3.18 (1.25)	1.91 (0.75)
	N4-2	32.39 (12.75)	26.21 (86.00)	3.18 (1.25)	1.91 (0.75)
	N4-3	38.10 (15.00)	30.78 (101.00)	3.18 (1.25)	1.91 (0.75)
	N4-4	43.82 (17.25)	35.35 (116.00)	3.18 (1.25)	1.91 (0.75)
	N4-5	49.53 (19.50)	39.62 (130.00)	3.18 (1.25)	1.91 (0.75)
	N4-6	55.88 (22.00)	44.20 (145.00)	3.18 (1.25)	1.91 (0.75)
Nitrator 6	N6-1	22.86 (9.00)	22.25 (73.00)	2.22 (0.88)	3.0 (1.59 (0.63))
	N6-2	26.67 (110.50)	26.21 (86.00)	2.22 (0.88)	3.0 (1.59 (0.63))
	N6-3	32.39 (12.75)	31.69 (104.00)	2.22 (0.88)	3.0 (1.59 (0.63))
	N6-4	38.10 (15.00)	36.27 (119.00)	2.22 (0.88)	3.0 (1.59 (0.63))
	N6-5	43.82 (17.25)	41.15 (135.00)	2.22 (0.88)	3.0 (1.59 (0.63))
	N6-6	48.26 (19.00)	45.72 (150.00)	2.22 (0.88)	3.0 (1.59 (0.63))
Nitrator 8	N8-1	26.67 (10.50)	9.75 (32.00)	7.30 (2.88)	1.1 (1.91 (0.75))
	N8-2	32.39 (12.75)	11.58 (38.00)	7.30 (2.88)	1.1 (1.91 (0.75))
	N8-3	38.10 (15.00)	13.71 (45.00)	7.30 (2.88)	1.1 (1.91 (0.75))
	N8-4	43.82 (17.25)	15.54 (51.00)	7.30 (2.88)	1.1 (1.91 (0.75))
	N8-5	44.53 (19.00)	17.37 (57.00)	7.30 (2.88)	1.1 (1.91 (0.75))
	N8-6	55.88 (22.00)	19.50 (64.00)	7.30 (2.88)	1.1 (1.91 (0.75))

^aTube material in accordance with SAE specification J526B

^bAll coils above utilized as active heat exchange surfaces

^cCenter-to-center diameter of coil

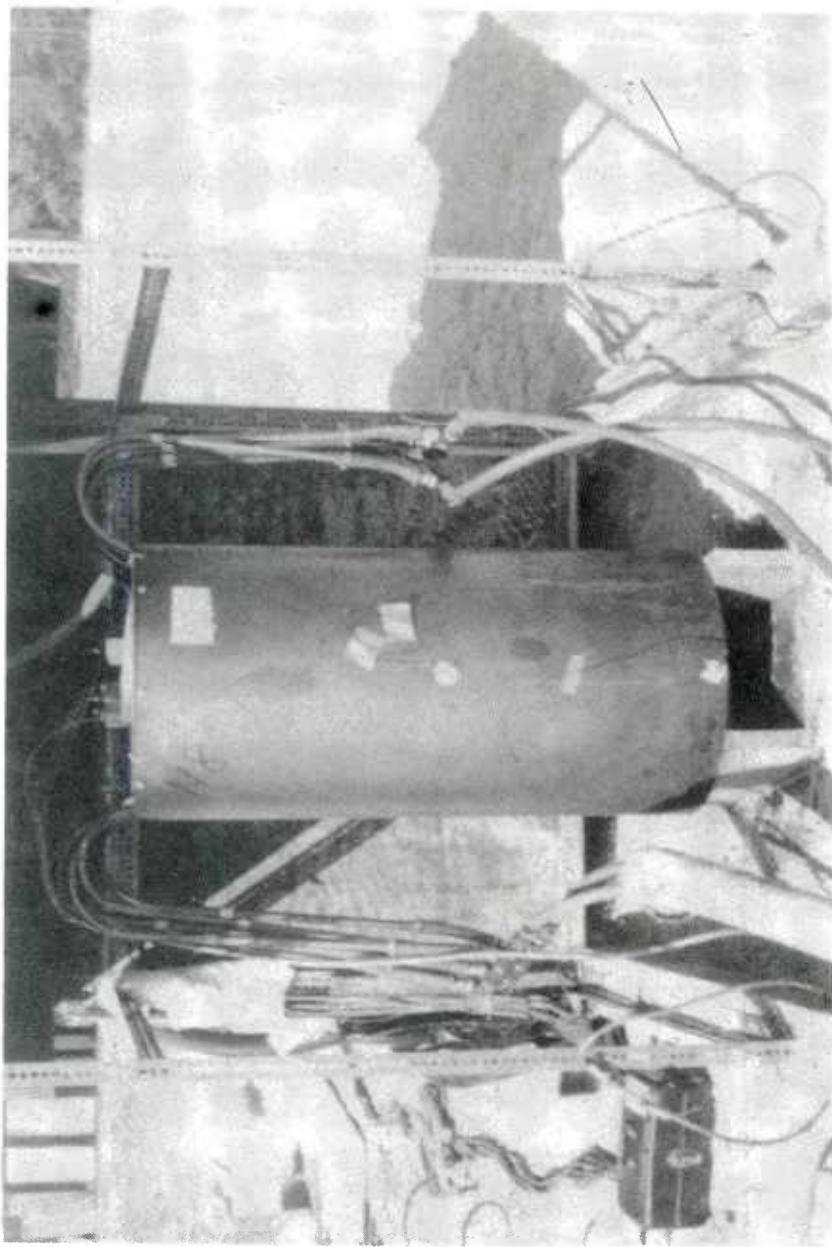


Fig 17 Nitration reactor in field with view of the heat transfer coil
leads, manifolds, and water hose connections

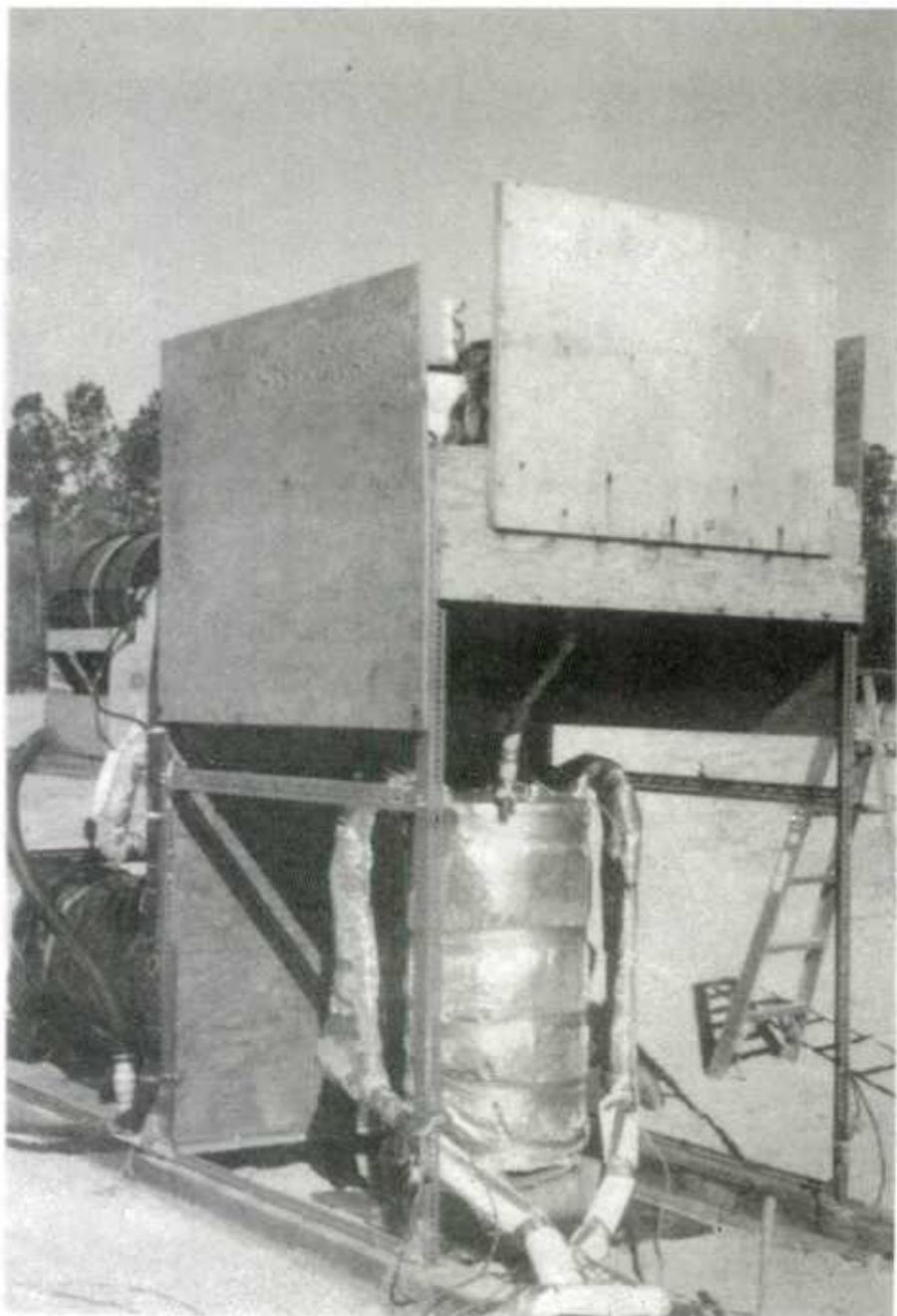


Fig 18 Relative position of melt sled and reactor prior to remote withdrawal operation

In preparation for a test the dugout was covered with sheets of plywood and a shallow layer of ground. The layer of ground was graded level with the surrounding terrain.

In some cases, the equipment or procedures used in this test series were similar to those used in the KOP test series. In these events, reference is made to the appropriate section of this report for the detailed description.

2.3.2.1 Pressure Measurements

Blast pressure measurements were made along two orthogonal lines designated, line A and line B. The intersection of the gage lines was designated ground zero and the distance to the gage locations was measured with respect to this point. The gage line area was compacted sand fill, graded to form a relatively flat surface. The transducers were mounted in precast concrete blocks. The blocks were embedded in the sand so that the top surface was flush with the surrounding area. The concrete blocks contained a gage mounting adapter on the top surface and a gage cable exit port near the bottom surface. The gage cables were run underground in the near field and aboveground in the far field to a field patch bay. The patch bay, in turn, was connected to the instrumentation patch panel in the control center.

Pressure Transducers: The pressure transducers employed were piezoelectric type units manufactured by Susquehanna Instruments. The two types of transducers used were Model ST-4, using tourmalene as its sensing element, and Model ST-2 using lead metaniobate as a sensor. Each transducer was equipped with a PCB Piezotronics Model 401A or 402A voltage-follower amplifier. Two multichannel power units, PCB 483A, were used to supply constant current excitation to the voltage-follower amplifiers. Capacitive coupling was used to block the DC bias voltage and to couple the data signals to the recorders.

Calibration Procedure: The physical calibration technique was used where pressure is applied to the transducer from the field location. The calibration fixture consisted of a compressed air supply, a plenum chamber, a bourdon gage and a solenoid valve. This system was transported to each gage location where it was used to apply a known pressure pulse to the transducer. The system had a range of zero to 150 psig and the rise time of the pressure pulse was about 15 msec.

The transducers were calibrated at the pressure level equivalent to the anticipated test peak overpressure. Calibration data signals were monitored at the control center and the gain level of the recording device was adjusted to the desired level. Having established the proper recording level, a calibration trace was recorded. This recording was used for data reduction.

Recording Instruments: The pressure-time data were recorded on magnetic tape and on transient recorders. The magnetic tape recorders were the Honeywell 9600 and the Sangamo 4700. The transient recorders used were Biomation Corp, Type 610A and 610B.

The Honeywell 9600 recorder conforms to IRIG Eide Band Group II. The frequency response, in FM mode, is zero to 500 kHz at a recording speed of 305 cm/sec (120 ips). The Sangamo 4700 is an IRIG intermediate band recorder with a frequency response of zero to 20 kHz at a recording speed of 152 cm/sec (60 ips), in FM mode.

The Biomation 610 Transient Recorder consists of a variable gain amplifier, a high speed A/D converter, a digital memory and a D/A converter. These main circuit elements are controlled by trigger and timing circuits. The recorder has the capability for digital and analog outputs. Pre-trigger recording was used to record the base line level prior to the arrival of the blast pressure at the gage location. The signals were recorded on 6 bit, 256 word over a selectable time range from 10 to 5 sec.

Data Reproduction: Data recorded on magnetic tape were reproduced on a Honeywell 1612 Vesicorder. The Vesicorder was equipped with 13 Type M1650 galvanometers, having a flat frequency response zero to 1000 Hz. The reproduced speed for both magnetic tape recorders was 19 cm/sec (7.5 ips). The effective frequency response of the oscillograph print-outs were 16 kHz and 8 kHz for the Honeywell 9600 and Sangamo 4700 recorders respectively.

Data recorded on the transient recorders were displayed in analog and digital form. A CRT display was used to obtain the analog data and the digital information was output to a printer. Hardcopy of the data was obtained in analog and digital form.

A break wire (BW) signal was used to enable a time base generator at the instant the charge was detonated. The time base signal was recorded and used in data reduction to determine time-of-arrival of the blast wave of the gage locations,

Transducer Location and Recording Assignment: Table 14 shows the type of transducer assigned to the gage positions. The distance shown is with respect to ground zero (i.e., test item location). The positioning of the transducers by type was the same on both blastlines. The transducer assignments shown were for the initial fielding of the instrumentation system.

Table 14
Transducer location and recording assignment

Gage position	Location m (ft)	Transducer type	Recorder		
			Honeywell 9600	Sangamo 4700	Biomation 610
1A 1B	4.27 (14.0)	ST-4	x		x
2A 2B	5.82 (19.1)	ST-4	x		x
3A 3B	8.23 (27.0)	ST-2	x	x	x
4A 4B	13.10 (43.0)	ST-2		x	
5A 5B	19.10 (62.5)	ST-2		x	
6A 6B	39.10 (128.4)	ST-2H		x	
7A 7B	68.30 (224.1)	ST-2H		x	
BW	0		x	x	

2.3.2.2 Detonation Velocity Measurement

Three instrumentation methods were used to monitor detonation velocity: ionization probes, shock pressure time-of-arrival gages, and continuous velocity probes.

Systems used for the detonation velocity measurements are described in the following paragraphs.

Ionization Probes: The ionization probe assembly consisted of six pairs of tensileter insulated copper wires cut to lengths, with the conductor exposed, thus providing measuring stations at 18 or 20 cm (7 or 8 inch) intervals depending on the test requirements. The probe assembly was placed inside the draft tube and held in place by a mounting adapter attached to the cover plate. Epoxy cement was used to hold the glass tube to the wall of the draft tube.

The ionization probe signal condition circuitry described in subsection 2.2.2.2 was used in this test series. Individual signal conditioning units were used, figure 11, and the signals were recorded on separate oscilloscope channels. Three dual beam oscilloscopes, Tektronix Model 5444, equipped with C-59 cameras, were used for this purpose. The oscilloscopes were triggered by a probe embedded in the booster charge.

The use of separate recording channels to record time-displacement data may appear to be extravagant. However, the occurrence of spurious signals in some of the earlier multiplexed data caused difficulty in data interpretation. The present scheme will provide a clear indication of the arrival time at each measuring station.

Shock Pressure-Time of Arrival: The sensing element for this measurement technique is a composition carbon resistor. When the resistor is subjected to a shock-pressure wave, the resistance value decreases rapidly, on the order of a microsecond. The amount of resistance change is dependent on the amplitude of the shock wave (reference 9).

The resistors used in this application were 0.1 watt 470 ohm \pm 5 percent composite carbon resistors. The resistors were force fitted into holes drilled into a strip of teflon. The resistors were transversely mounted to the long axis of the strip at 20 cm (8 inch) intervals. The resistor leads were insulated with flexible tubing and connected to teflon over teflon shielded cable.

Machine screws were used to attach the gage assembly to the outside wall of the draft tube. The shielded cables were run to the conditioning circuitry located in the dugout.

The conditioning circuitry consisted of a constant voltage supply and a common current sampling resistor, thus providing a multiplex signal used to determine the time-dependent relationship of the shock wave. The data was recorded on a Biomation 610 Transient Recorder.

Continuous Velocity Probe: This probe is patterned after the continuous velocity probe developed for the Instrumented Card-Gap Test (reference 10). The basic concept is similar, however certain design changes were required to provide a transducer suitable for use in the TNT nitration reactor tests.

The continuous velocity probe is illustrated in figure 19. The resistance wire, partially insulated by a space wrapped nylon thread, was inserted into a small-bore 304s stainless tube. The tube and resistance wire were crimped at the closed end to form an electrical junction. The resistance wire was fed through a copper crimp-on connector and, in turn, through a nylon insulated guide at the connector end. PVC insulated lead wires were attached to the copper connection and to the resistance wire as shown in figure 19. Epoxy coating was used to provide a firm lead wire anchor. The resistance of the center wire was 272 ohms/m (83 ohms/ft) and the length of the probe is 1.22 m (4 ft) thus providing a probe resistance of 332 ± 0.5 ohms. A constant current supply was used to provide power to the probe. The power supply chassis contains a calibration resistor, R_1 , used to adjust the scale factors on the recording oscilloscope.

The performance of the probe was tested by using datasheet C-2 (63% PETN, 8% CN). A strip of datasheet 0.21 cm (0.083 inch) x 2.54 cm (1.0 inch) x 1.27 m (50 inches) was cemented to a wooden strip. The probe was depressed into the datasheet. A second layer of datasheet was placed over the probe so that it was virtually encapsulated in the datasheet. The booster charge used was a 1.27 cm (0.5 inch) x 1.27 cm (0.5 inch) tetryl pellet, fixed by a number 6 blasting cap. The published detonation velocity for datasheet C-2 is 7000 m/sec (22,960 fps).

Two probes were tested. The detonation velocity as determined by the experimental data is 7088 m/sec (23,249 fps) which is in good agreement with the published value. The continuous velocity probe, in its present design, has reasonable structural integrity. Two probes were installed on the inside surface of the draft tube. The probes were held in place by using stainless shim stock to clamp the probe. The stainless shim stock was then spot welded to the wall of the draft tube.

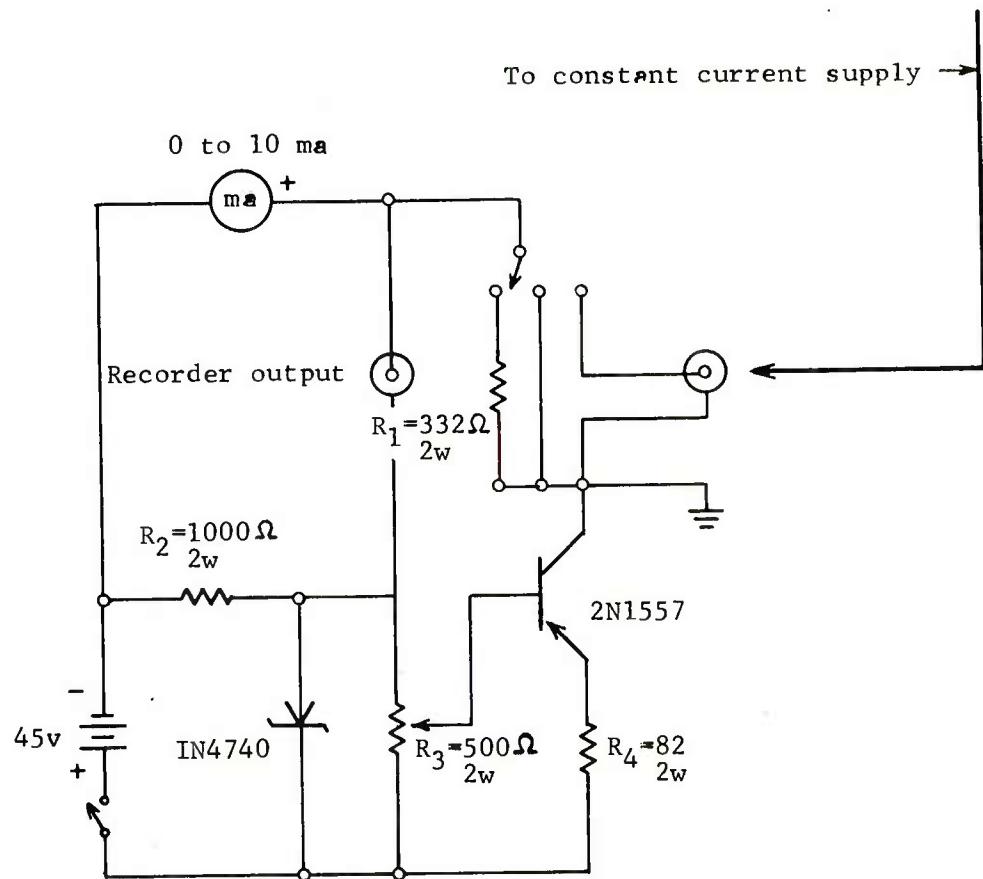
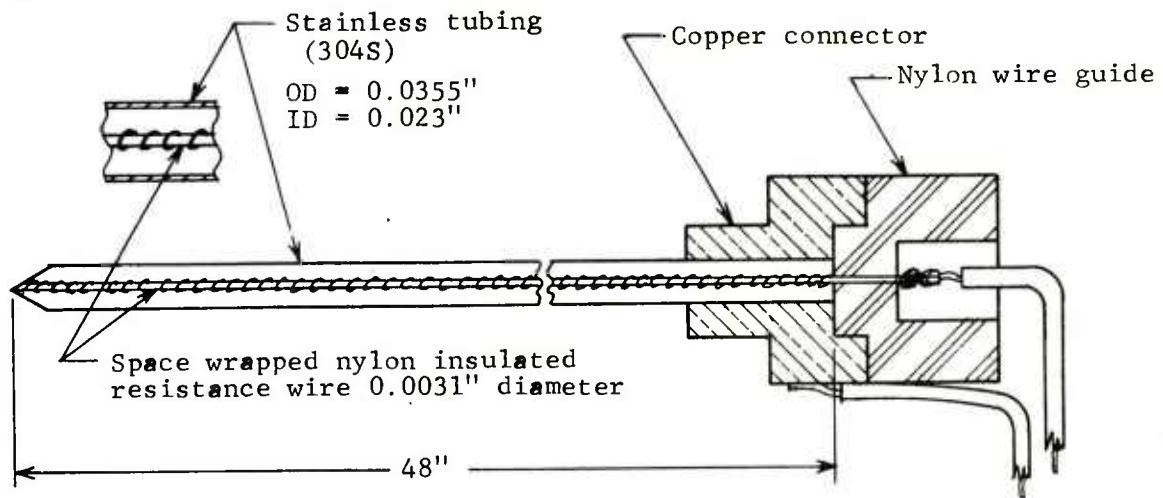


Fig 19 Illustration of the continuous velocity probe

Two dual beam oscilloscopes were used to record the wave velocity. One probe output was recorded on the top beam of each oscilloscope and the second probe was recorded on the lower beam. The oscilloscopes were triggered separately; one from the BW system and the other from the booster ion probe. Finally, one probe output was dual recorded on a Biomation channel to provide additional backup.

2.3.2.3 Temperature Measurements

Temperature measurements were made at six locations; in the hot and cold water reservoir tanks, in the DNT and TNT melt/mix kettles and at two positions in the reactor tank. Reference junctions were located in the steel building, on the melt sled and in the field signal conditioning dugout. The thermocouples used were the same type and configuration as those used on the KOP test series and described in subsection 2.2.2.3.

The water temperature was monitored by installing thermocouples in the side wall of the hot and cold reservoir tanks. Thermocouple leads were run to the reference junction located in the steel building. Copper leads were run from the cold junction, through the field patch bay (Pad C) and eventually to the patch panel located in the control center.

Thermocouples were mounted in the covers for the DNT and TNT melt/mix kettles. These units were mounted so that when the covers were in place, the measuring junctions were submerged in the melt. The reference junction was installed on the melt sled and shielded pair, copper cable was used to conduct the signals to a terminal board located in the field signal conditioning dugout. A pullaway splice was used to disconnect the lead wires when the melt sled was removed from the test area.

The reactor tank contained two thermocouples; one near the bottom and the second at the center of the side wall. These units were installed in mounting holes drilled in the tank wall and were held in place with epoxy cement. Thermocouple extension lead wire was used to connect these units to the reference junction, located in the dugout. Data signals from the dugout were routed through Pad D to the instrumentation patch panel.

The thermocouple voltage signals were recorded on a Tracor-Westronics multipoint chart recorder. The voltage measurements were converted to temperature readings by using a standard reference table.

The temperature measuring circuitry was tested by applying a millivolt source to each of the transmission cables in the field and noting the recorded level. Actual temperature measurements were verified by direct comparison of the thermocouple readings to a mercury-glass thermometer.

2.3.2.4 Agitator Shaft Speed Measurements

A permanent magnet DC motor with an SCR speed control was used to drive the agitator shaft. The agitator shaft speed was monitored by the simple and reliable magnet/reed switch technique described in subsection 2.2.2 (reference 9). The electronic counter used to display the shaft speed was located in the control center, near the SCR speed controller. This arrangement provided a convenient method for monitoring and adjusting the agitator shaft speed.

As previously stated, the shaft speed measurements and temperature measurements were used to establish and verify the initial operating conditions. The operating conditions of the nitrator systems for each test series is provided in table 15.

Table 15
Operating conditions

Reactor	TNT/DNT (kg (1b))	RPM	Temperature °C (°F)	DNT Reaction time
Nitrator 4	33/54 (72/120)	1450	77 (170)	10 min
Nitrator 6	91/0 (200/0)	1068	102 (215)	---
Nitrator 8	91/0 (200/0)	1450	102 (215)	---
Acid Wash	91/0 (200/0)	625	85 (184)	---

2.3.3 Support Equipment and Test Site

To accomplish the large-scale experiments, the test area had to be prepared and several support systems had to be designed and constructed. These included the heat transfer system, the TNT/DNT melt process, the electrical control system, and the acid transfer equipment.

2.3.3.1 Heat Transfer System

Just as in the small-scale tests, a quick response heat transfer system was required to provide hot water to the coils inside the test vessel to maintain the mixture temperature above the nitrobody melting point and to provide cold water to cool the mixture during nitration reactions. The heating/cooling system is diagrammed in figure 20. It consists of the hot and cold water reservoirs, centrifugal pumps, control elements and the heat transfer coils inside the test vessel.

The hot and cold water reservoirs are shown in figure 21 with their centrifugal booster pumps. The reservoirs were each a 208 liter (55 gallon) drum modified to accommodate pipe connections. The hot water reservoir sat above two propane burners and contained four immersion heaters. Each propane burner was rated for 760 watts (26,000 Btu/hr). The immersion heaters each provided 4500 watts (15,363 Btu/hr). The cold water reservoir was filled with cool tap water prior to each test.

Hot and cold water hoses were buried between reservoirs and the control box near ground zero. The hoses were insulated and wrapped with plastic sheet to keep out moisture. The hose lines are shown in figure 22 before being covered with soil.

The control box was located approximately 7.62 m (25 ft) from ground zero. This is shown in figures 23 and 24. Several rows of plastic pipes were located between the control box and the explosion center to act as blast attenuators and protect the pumps and solenoids buried inside the box during the detonation. The control box contained two 746 watt (1 hp) centrifugal pumps. Each pump provided water flow to one of the two coil intake manifolds at the test vessel. Four normally open and four normally closed solenoid valves were located in the box and were used to switch between the heating and cooling cycles. During heating, only the two pumps were operating, whereas during cooling all eight solenoids as well as the two pumps were energized. The box was located near ground zero to minimize the response time for the transition between heating and cooling operations.

At the test vessel, the six heat transfer coils were divided into two sets, each connected in parallel to minimize flow resistance. Each set of coils was connected to an inlet manifold which received water from one of the pumps in the control box. Each set was also connected to an exit manifold which fed water into one of the hoses returning water to the reservoirs. The manifolds were located outside of the reactor tank to avoid a possible acid-water reaction in case of a leak at a pipe connection.

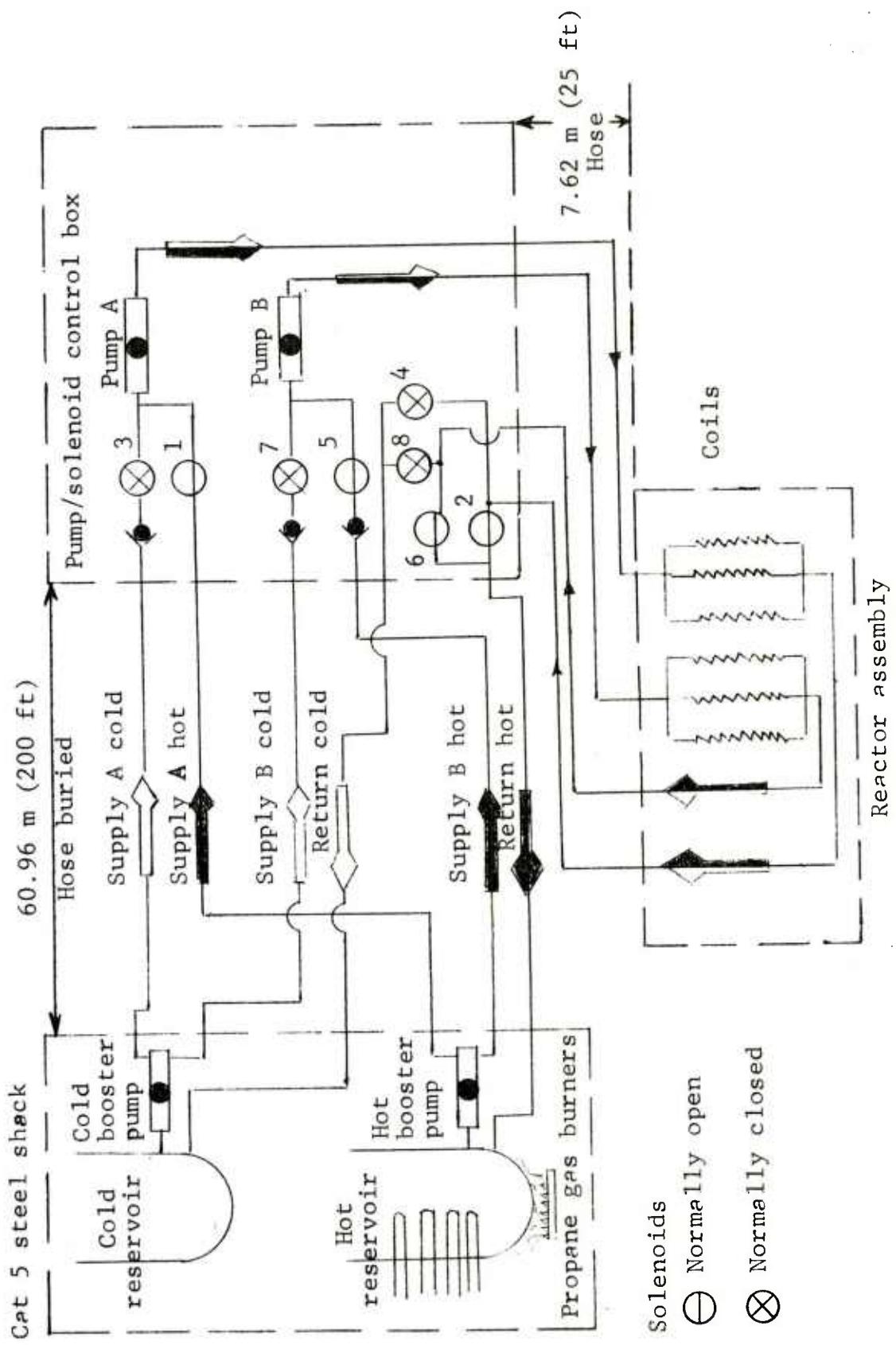


Fig 20 Temperature and flow control schematic



Fig 21 Hot and cold water reservoirs with corresponding hose and booster pumps



Fig 22 Insulated hose lines and electrical line layout

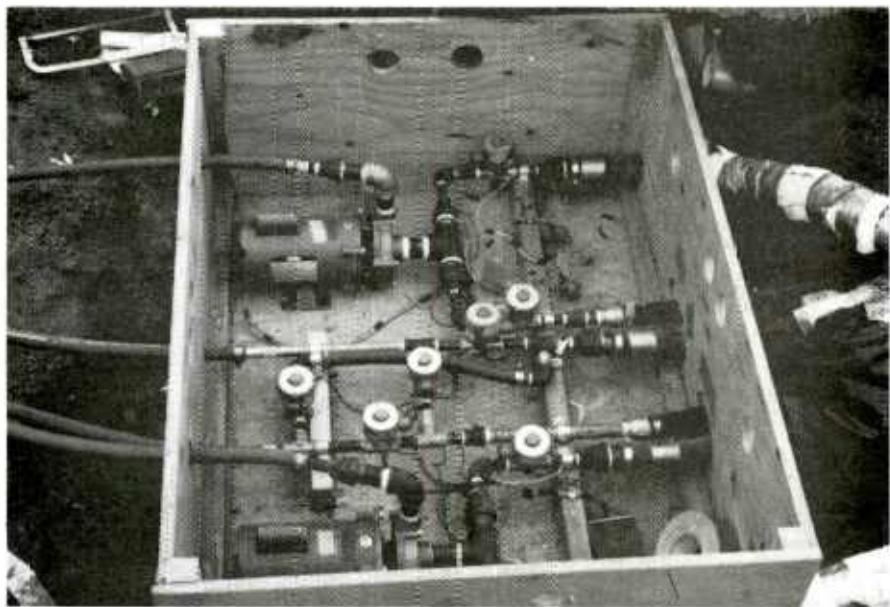


Fig 23 Control box with inline water pumps and solenoid for heat-cool cycle regulation

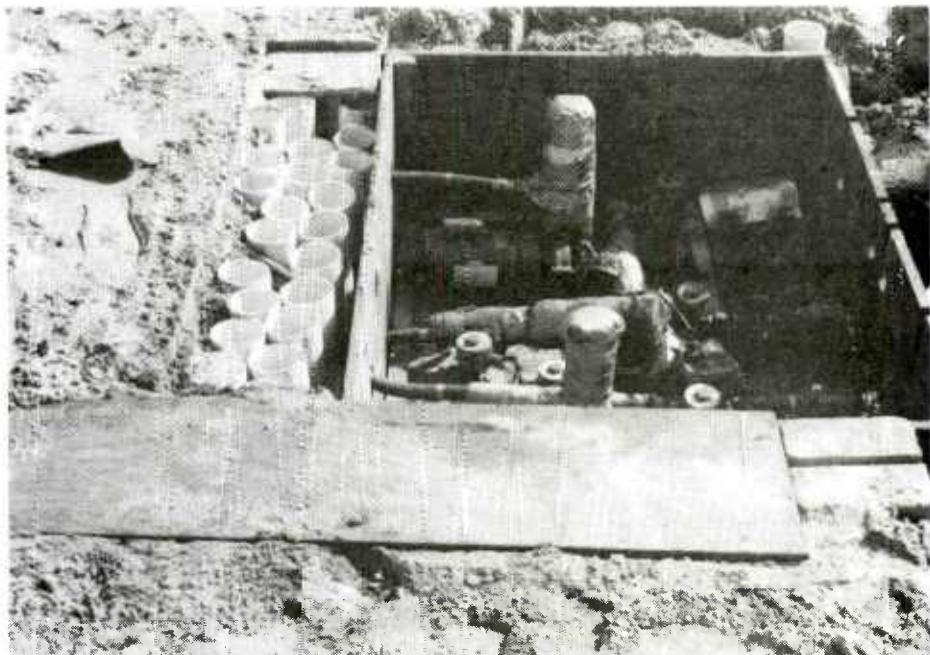


Fig 24 Control box with plastic pipe (air-filled) shock attenuators

Sufficient heat was provided during the heating cycles to maintain the test vessel at 100°C (212°F). Figure 25 shows the test vessel temperature time-history acquired for the nitrator 6 coil configuration. A corresponding cooling cycle is given in figure 26 for the nitrator 8 coil arrangement.

2.3.3.2 TNT/DNT Melt Process

For the large-scale tests, it was necessary to design a remote meltdown system. TNT and DNT were melted in steam kettles positioned directly above the test vessel in the field. The steam kettles and supplementary steam generator were on a moveable cart fabricated from Dexion steel angle. The cart was built on two large solid wooden skis, 0.15 m x 0.15 m x 3.66 m (6 inch x 6 inch x 12 ft). The wooden skis provided mobility to the cart and allowed it to be pulled to a protected area prior to the detonation of the test vessel. The cart weighed about 680 kg (1500 lb). It was connected to a truck by a long wire cable and could be pulled to safety 61 m (200 ft) in 5 min and 15 sec. Components on the sled were protected by 1.91 cm (3/4 inch) thick plywood boards fastened to the sled framework.

Figure 27 shows the melt sled with the steam kettles and steam generator system. A schematic diagram of the steam cycle is shown in figure 28. The steam generator (Citation type, 454 liters per hr (120 gallons per hr) saturated steam at 121°C (250°F)) was located on the lowest level of the stair shaped sled.

Two tanks were positioned just above the steam generator. A 300 liter (80 gallon) flash tank was required to allow expansion of the hot condensate return and to act as a reservoir for water fed into the steam generator. The steam generator itself had a 30 liter (8 gallon) capacity water tank which was connected in series with the 300 liter (80 gallon) flash tank. In addition, a 114 liter (30 gallon) fuel tank was located above the steam generator on the sled. The small fuel tank on the steam generator was bypassed in lieu of the 114 liter (30 gallon) tank.

On the highest level of the cart, two 288 liter (76 gallon) capacity, 0.61 m (2 ft) diameter steam kettles were positioned. These were custom-made from 303 stainless steel. Each kettle was sized to hold at least 45.4 kg (100 lb) of flake TNT or powder DNT explosive prior to meltdown. The 5.1 cm (2 inch) diameter outlet from each kettle was at the bottom of the hemispherically shaped container and was connected to the test vessel through a flexible hose.

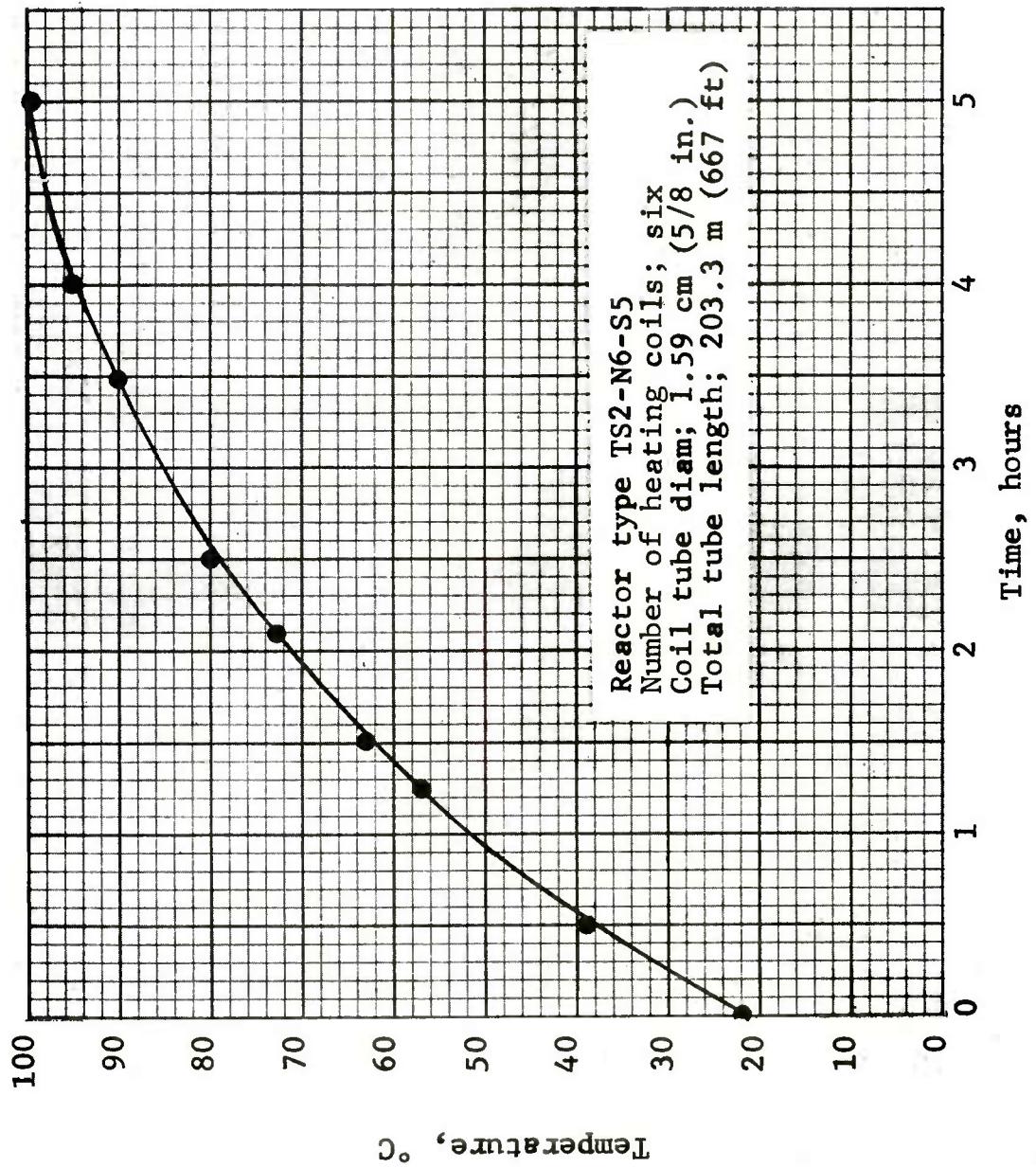


Fig 25 Nitrator heating cycle (nitrator TS2-N6-S5, typical)

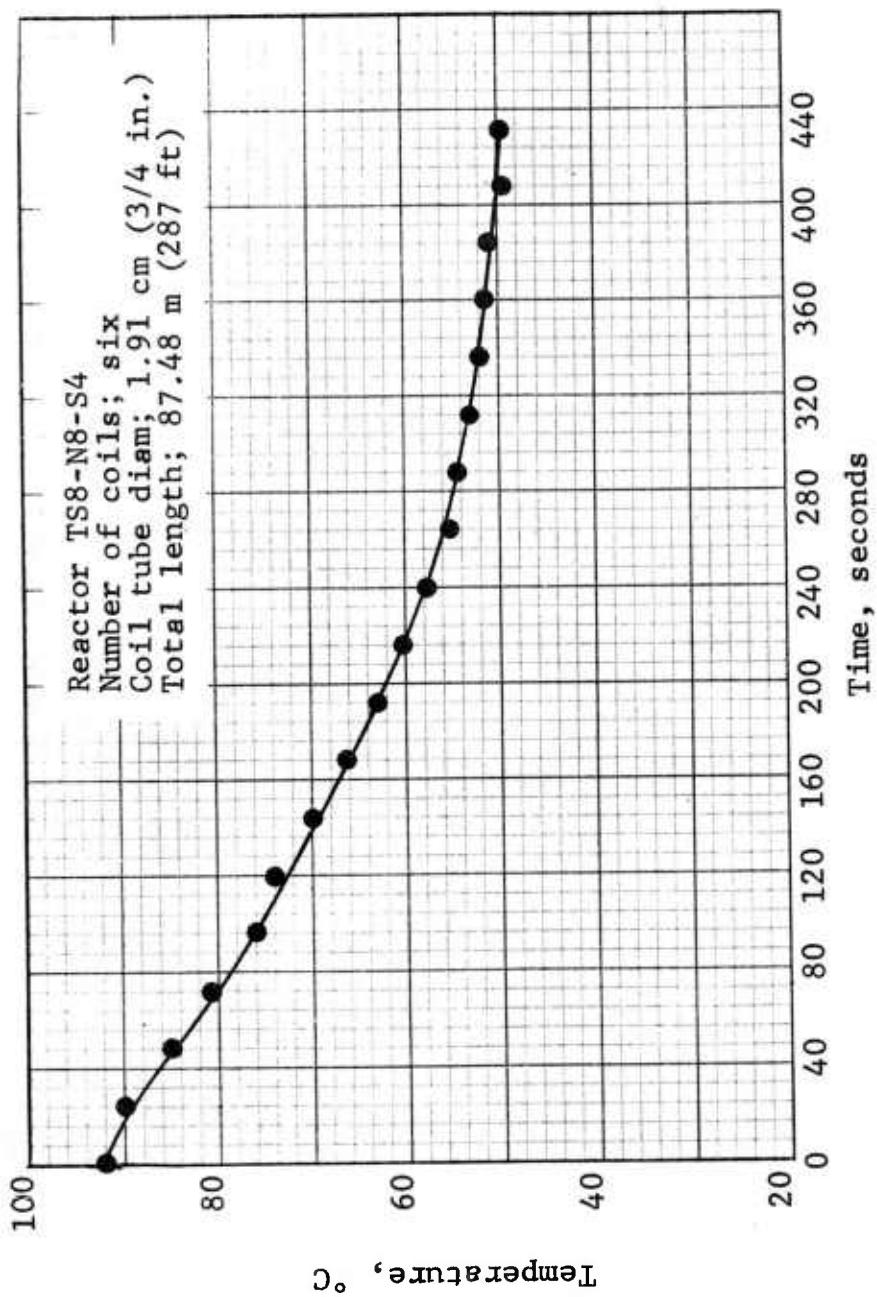


Fig 26 Nitrator cooling cycle (nitrator TS8-N8-S4, typical)



Fig 27 Movable sled structure with TNT/DNT melt kettles and steam generator system

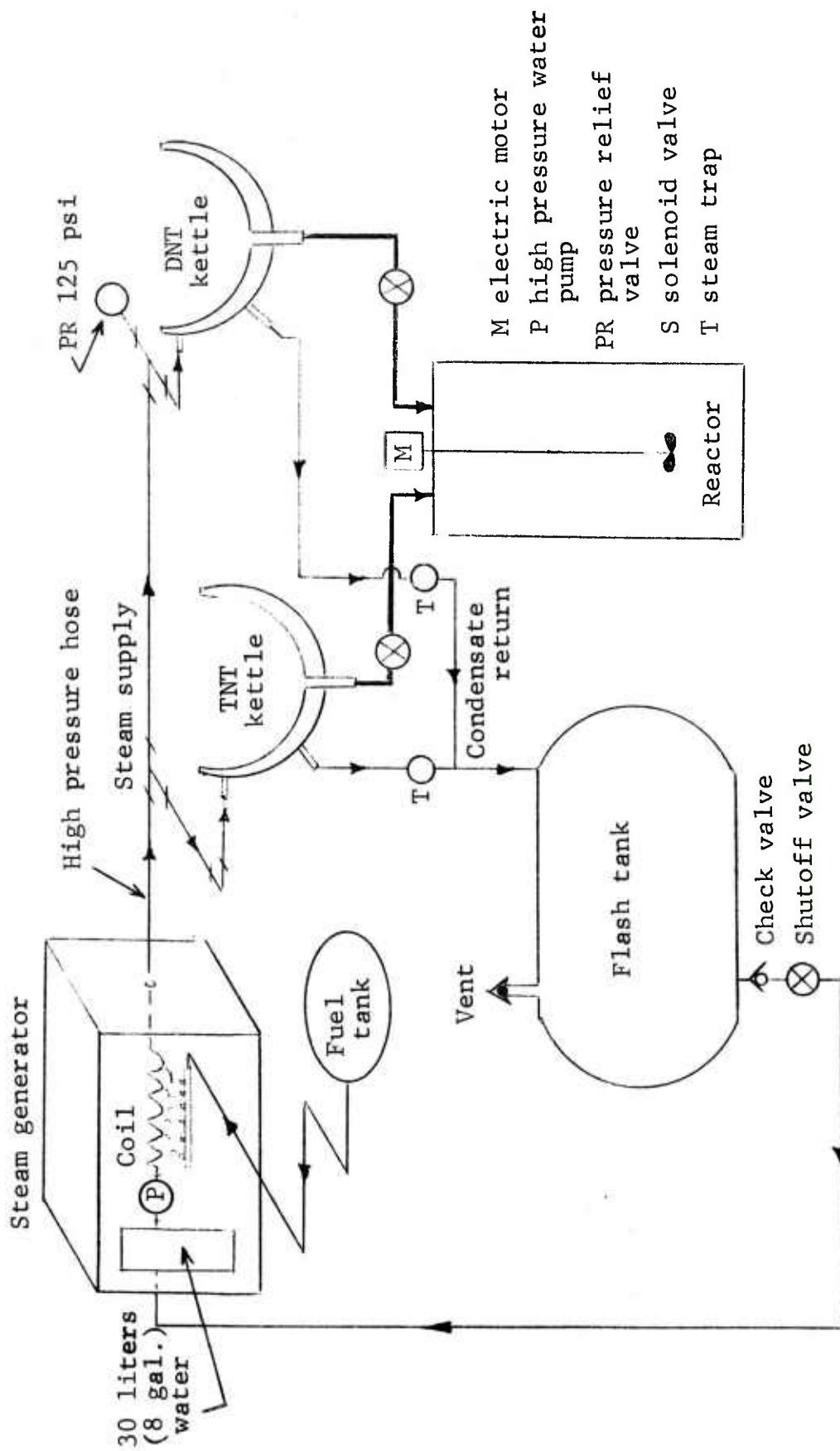


Fig 28 TNT/DNT melt-steam cycle

Normally closed solenoids prevented outflow of liquid TNT or DNT until the solenoids were energized. Heating tapes were wrapped around the solenoids and pipelines to prevent crystallization of the explosives in the lines and consequent blockage. The piping leading from the melt kettles to the test vessel was flexible to allow the pipes to slide out of the mock reactor without pulling the tank over upon cart removal.

The melt kettles were fit with wood covers to minimize heat losses. A 15 watt (1/40 hp) constant torque electric motor was bolted to each wooden cover. These motors slowly turned agitator rods to improve the melting process.

Electrical power and control was required for the steam generator, agitators, drop solenoids, and heating tapes. The required electrical power was provided by wires which were dragged behind the cart upon its removal from the field.

Calculations of the time required to melt TNT in the kettles indicated that 1 hr and 23 min would be more than adequate for melting the TNT flakes. A test in the field verified that 15 to 20 min was sufficient time to melt the explosives.

2.3.3.3 Electrical Control System

Electrical power was required for the following system components:

Control Elements

- television monitor for test site observation
- main pump and solenoid control box (hot and cold water for heat transfer)
- hot and cold booster pumps
- DC variable speed controller for reactor motor
- two rheostat dial controls for melt mixers
- variac control for heating tapes (two to three in parallel) on each reactor
- variac control for heating tapes on melt kettle feed pipe extensions
- TNT/DNT solenoid actuators (two electrical plug types)
- power to steam generator system

- firing circuit for booster initiation
- power supply for velocity probes

Indicator Elements

- rpm tachometer for reactor shaft rotation
- oscilloscope channels for velocity probe signals
- pressure measurement recording and conditioning equipment
- temperature recorder (six channels)
- indicator for reactor motor malfunction (sound pickups or volt meter)

Measuring Elements

- thermocouples (six)
- ion probes for velocity pickup (seven)
- continuous resistance velocity probe (two)
- pressure sensitive resistance switches for velocity pickup (six or seven)
- blast pressure transducers (14)
- Fastex camera and real time 16 mm camera coverage

Power was supplied at the instrumentation trailer and in the field by operating two 45 kw (60 hp) diesel driven generators. In figures 29 and 30 the electric circuit diagrams are provided for the reactor and melt sled control systems respectively.

2.3.3.4 Acid Transfer

The nitrating acid for each nitrator test was mixed at IITRI, Chicago. Stainless steel drums were procured to transport the acid to NSTL and store it until required during the tests. At the test site, acid transfer from the steel drum to the reactor was accomplished by gravity feed. The large stainless steel drum was raised onto a wooden support. A shutoff valve, hose, head fittings were secured to the acid tank openings. The speed which developed was sufficient to dump the entire contents in a relatively short period of time.

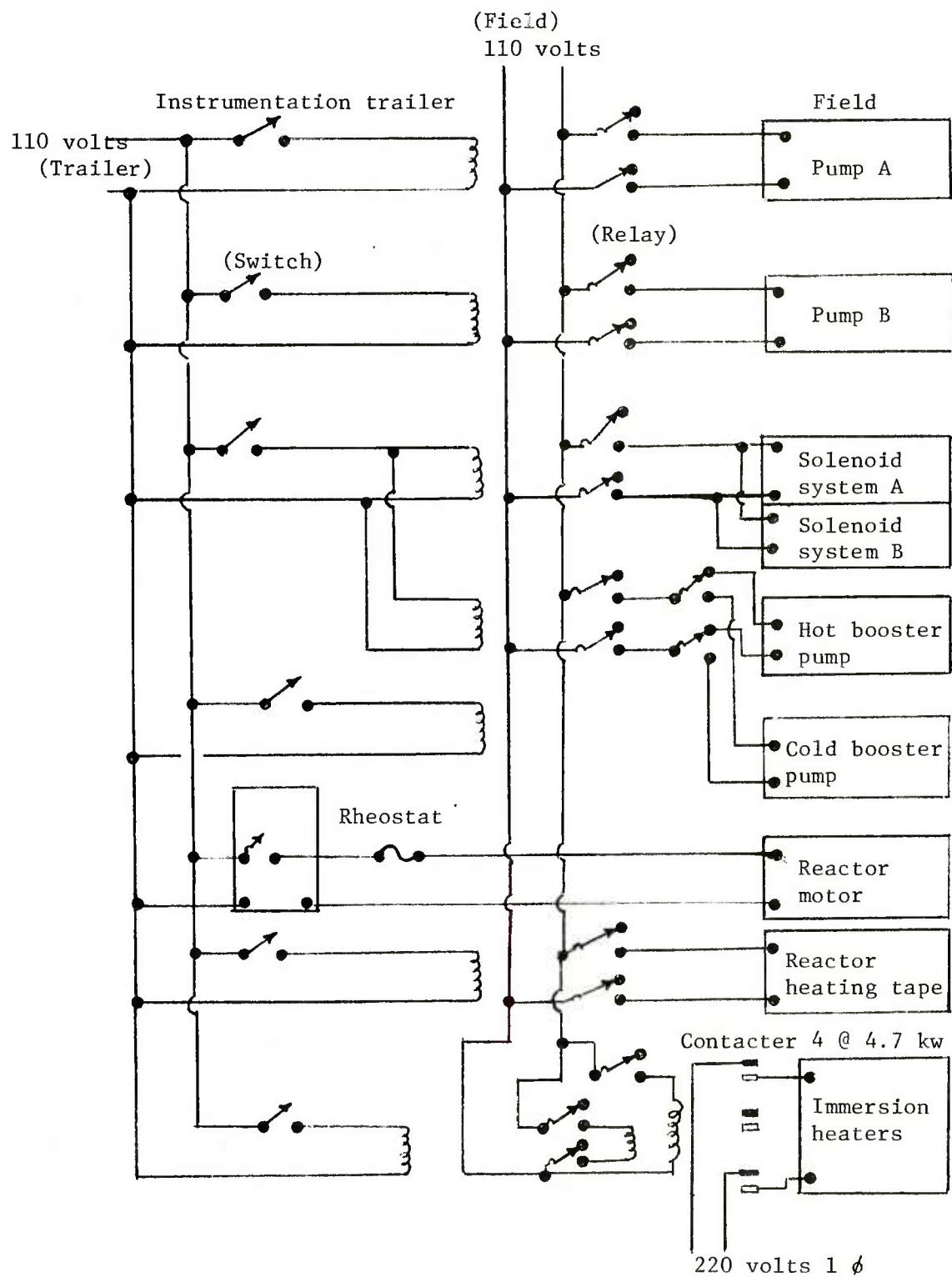


Fig 29 Electrical control system (reactor)

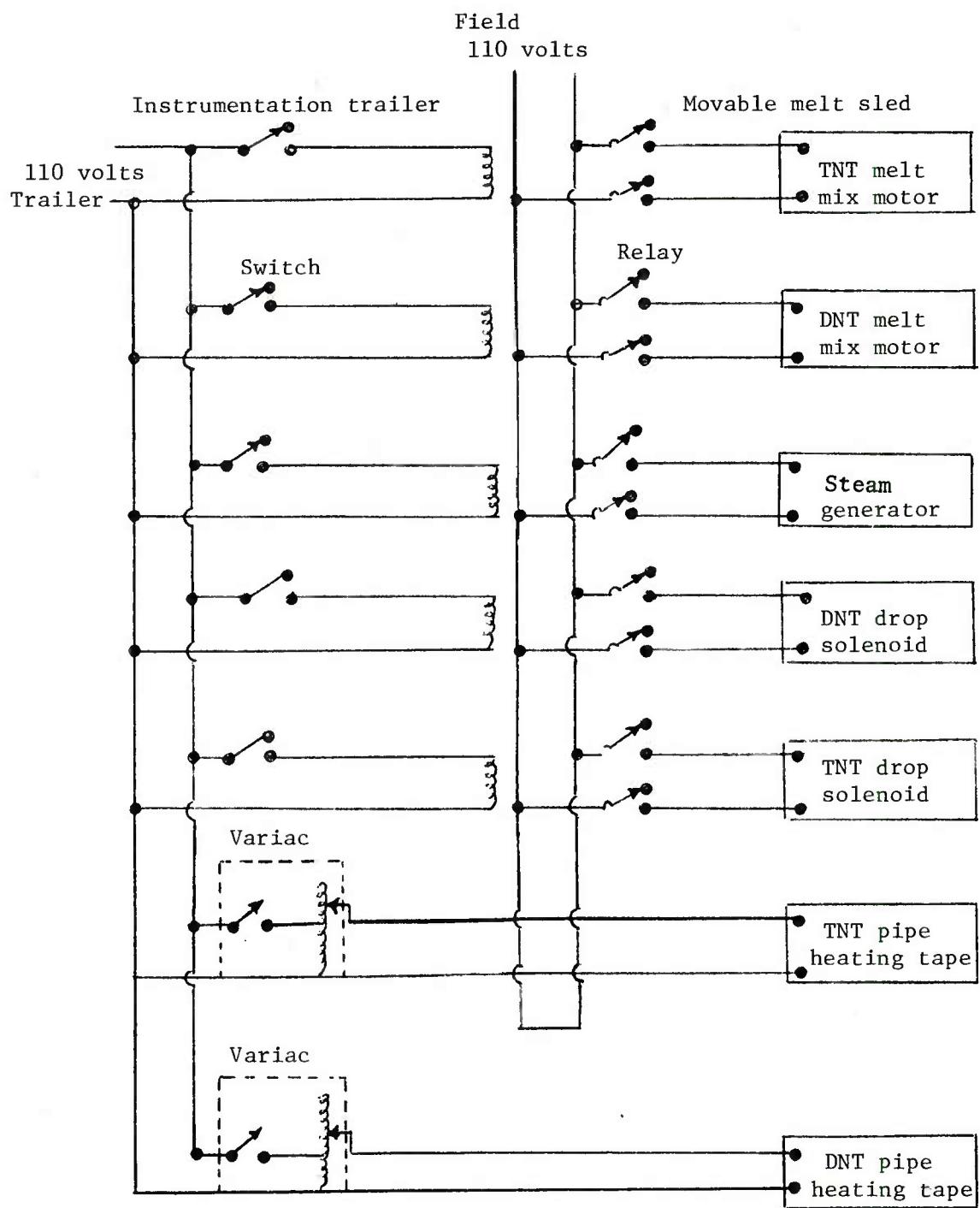


Fig 30 Electrical control system (melt sled)

The acid handling was performed by a two-man team with additional nearby television monitoring to assure a safe operation. Protective clothing which included acid resistant garments, rubber gloves, rubber boots, a gas mask and hood covers were worn by the personnel. An ample supply of water was made available for washdown should acid spashing occur. Video and radio contact was maintained until completion of the acid transfer. The acid transfer operation is shown in figure 31.

2.3.3.5 Test Area (NSTL)

A series of scaled 90.8 kg (200 lb) nitrobody reactor tests was planned for completion at the Edgewood Arsenal Resident Laboratory of the NSTL, Bay Saint Louis, Mississippi. The tests were performed at Kellar Range. The administrative and support assistance was furnished by the Edgewood Arsenal Resident Laboratory and the Computer Sciences Corporation. Design and technical supervision was furnished by IITRI personnel.

A sand mix was used to construct two gage lines (A and B lines) each 3.05 m (10 ft) x 76.2 m (250 ft) long. The sand mix provided a relatively clean ground surface around the pressure transducers. A schematic diagram of the test site is given in figure 32. Fourteen pressure transducers were mounted flush with the top surface of individual concrete block supports. The mountings for the four gages nearest to ground zero consisted of 0.305 m x 0.305 m x 0.305 m (1 ft x 1 ft x 1 ft) blocks. The remaining far field gages were mounted in 20.3 cm (8 inch) concrete cubes. Figure 32 shows the nominal gage locations, the arrangement of blast lines, the hoselines, and the steel storage building.

A steel building was situated approximately 40.6 m (200 ft) from ground zero. It was utilized as a protective structure for the booster pumps, hot and cold water reservoirs, propane gas burners, the two 45-kw (60 hp) generators, and the electrical relay control system. An area approximately 6.09 m x 60.9 m (20 ft x 200 ft) was cleared and rolled to provide a pathway for removal of the melt sled from the field. Along the pathway, a ditch 0.305 m x 0.61 m x 61 m (1 ft x 2 ft x 200 ft) was excavated for burying all the water hose lines and electrical lines.

Cables from the pressure transducer to the instrumentation trailer were buried in the immediate area of the charge and were laid on top of the ground the rest of the way to the instrumentation trailer. An earth revetment shielded the administrative and instrumentation trailers approximately 244 m (800 ft) from the charge.

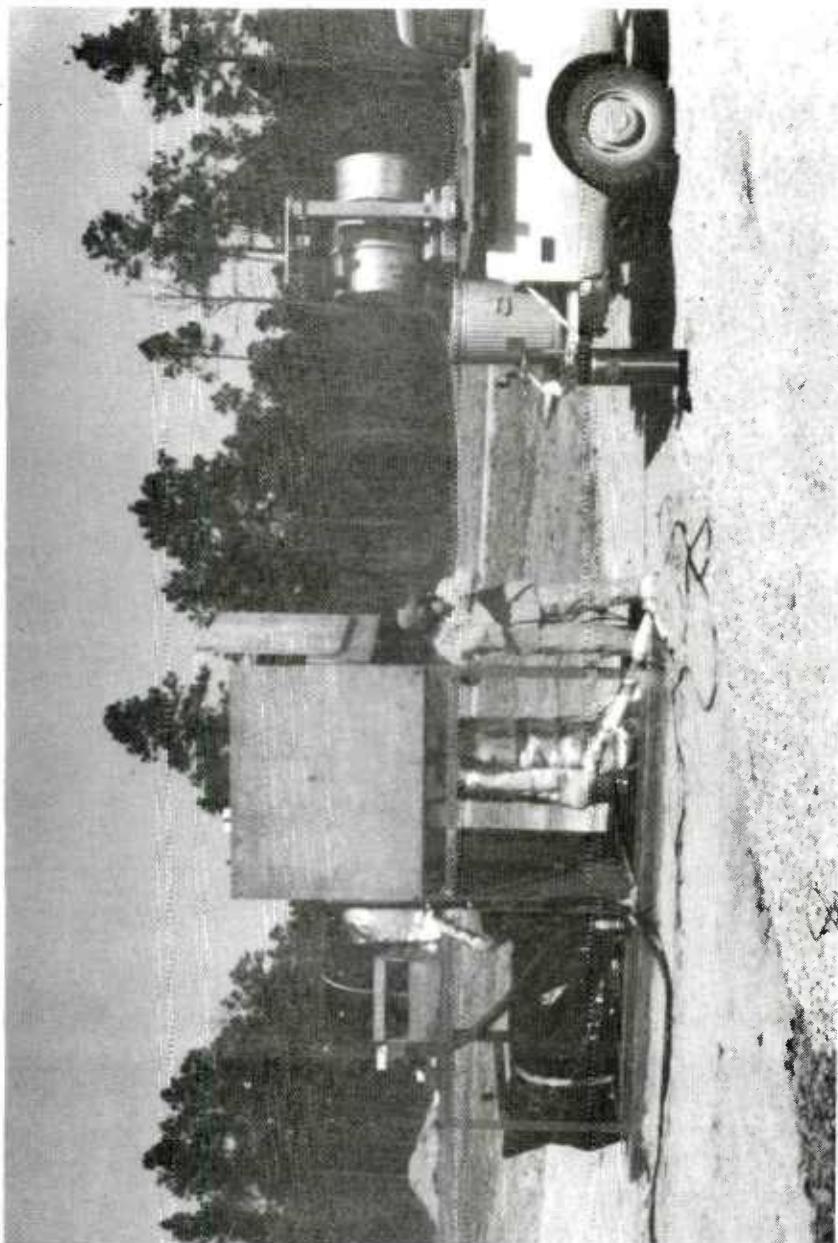


Fig 31 Acid transfer operation

Gage distance from ground zero

Gage	Distance m	Distance (ft)
1	4.3	(14.0)
2	5.8	(19.1)
3	8.2	(27.0)
4	13.1	(43.0)
5	19.1	(62.5)
6	39.2	(128.4)
7	68.3	(224.1)

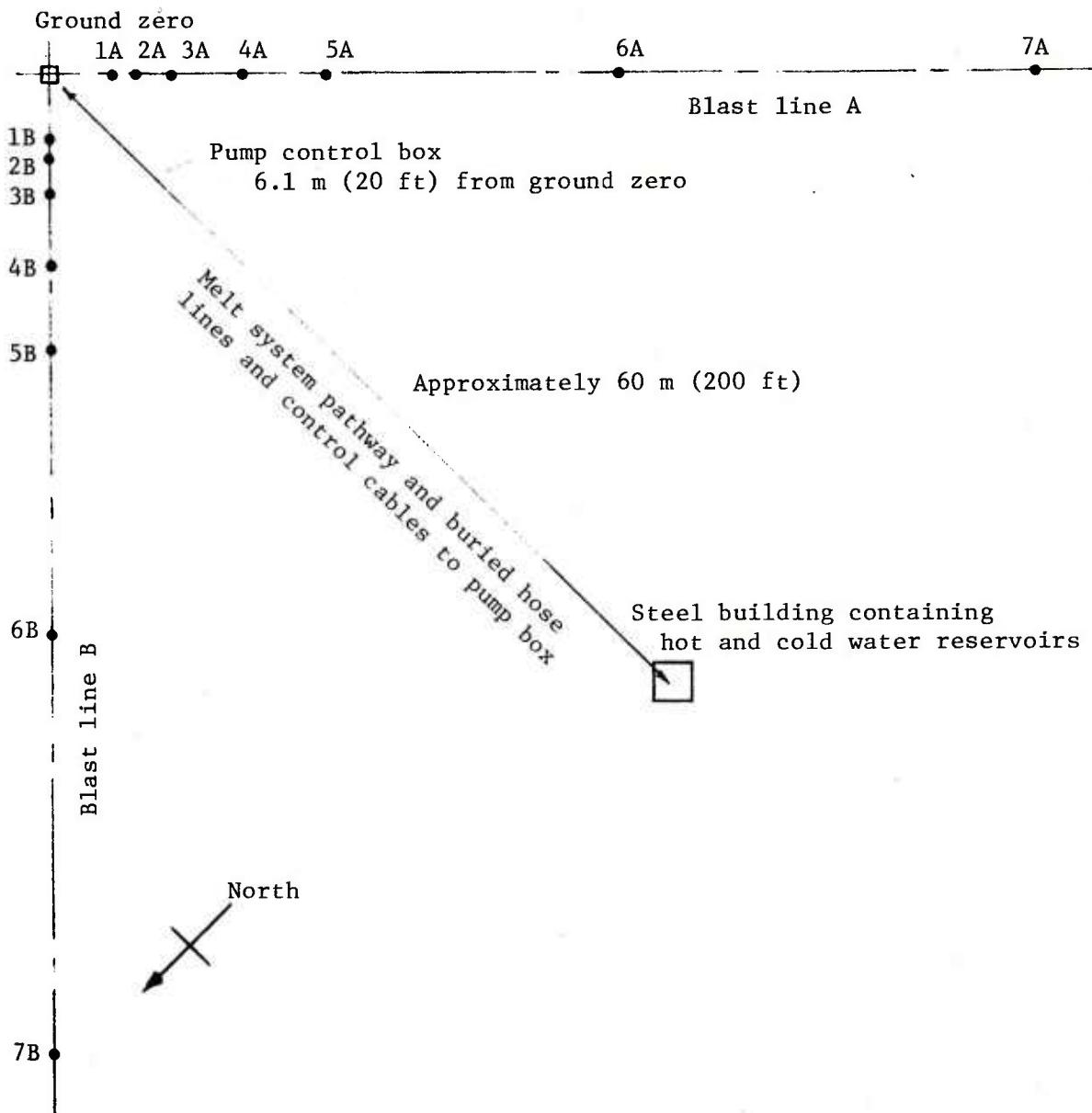


Fig 32 Site for large-scale tests

An access road was built parallel to the A-gage line leading to the reactor area. Drainage of the immediate test area was accomplished by building an interconnecting system of ditches using heavy equipment. Caution was taken to eliminate all obstructions from the blast field.

Reflection characteristics were investigated to assure a clean pressure front at each of the gage locations. Distances between known obstacles and gages were made large enough to ensure that arrival of reflected waves would occur well after the arrival of the initial shock front.

A television camera and monitor were provided so that the reactor and melt sled could be observed during the remote phase of the tests. To help ensure that all the liquid TNT and/or DNT was emptied from the steam kettles prior to removal of the sled, flags floating on corks in the kettles were used as a visual indicator during the dump operation. Photographic documentation of the tests included Fastex camera coverage at 4000 frames per second and still pictures before and after each shot.

3. TEST PLANS AND PROCEDURES

3.1 Schedule of Tests

The eight test series planned for this program are summarized in table 16. All tests involved 22.7 kg (50 lb) of nitrobody and were conducted at the IITRI explosives test site near LaPorte, Indiana, with the exception of shot 4 in test series 8. This test involved 90.8 kg (200 lb) of nitrobody and was conducted at the NSTL near Bay Saint Louis, Mississippi.

The first test in the program, not shown in table 16, was a trial nitrator 6 shot using a 5 percent booster. This system did not detonate, so it was decided to double the booster size in subsequent shots. In most cases, the 10 percent booster size was adequate and it was adopted as the standard. Because of the close contact between the booster and the layer of liquid TNT in the separator 6 configuration, a 5 percent booster was tried in the first test of the series. That system did not detonate and the 10 percent booster size was adopted for subsequent separator shots. Because of the apparent low output from early shots in test series 4, 5 and 8, 15 percent boosters were used in the later shots. All nitrator 4 tests except shot 2 utilized 10 percent boosters. Shot 2 of the series used a 5 percent booster and did not detonate. Once again it was seen that the TNT process components are quite insensitive to initiation and require a large booster size at least somewhere between 5 and 10 percent of the nitrobody weight.

3.2 Procedures for Small-Scale Tests

Table 17 outlines the general procedures used in the small-scale tests involving 22.7 kg (50 lb) of nitrobody per shot. These tests were conducted at the IITRI explosive test site at Kingsbury Ordnance Plant near LaPorte, Indiana.

The procedures in table 17 give the primary steps which were involved in each test. A few exceptions are discussed.

For the acid wash tank tests, the wash solution was mixed in the test vessel in the field. Water was measured and poured into the tank. A small quantity of acid was then slowly added to the water while temperature was being recorded and cold water was pumped through the heat transfer coils to control the reaction. When the reaction was completed, liquid TNT could be added to the wash solution and the test conducted.

Table 16

Schedule of tests

Test series description	Shot	% nitrobody weight	Booster	Acid or wash solution weight kg (1b)	TNT weight kg (1b)	Final DNT weight kg (1b)	Target reaction duration	Target mixture temperature	Target agitator rpm
1. Old nitrator 3A (batch process required)	1	10		24.8	14.9 (32.9)	7.8 (17.1)	3 min	77°C (170°F)	1710
	2	10		(54.6)					
	3	10							
	4	10							
2. Old nitrator 6 (simulated by mixing liquid TNT with nitrating acid)	1	10		37.1	22.7 (50.0)	None			
	2	10		(81.8)					
	3	10							
	4	10							
3. Old separator 6 (simulated by a rectangular box with nitrator 6 composition agitated and allowed to settle)	1	5		37.1	22.7 (50.0)	None			
	2	10		(81.8)					
	3	10							
	4	10							
4. Old acid wash tank inlet mixing compartment	1	10		4.0	22.7 (50.0)	None			
	2	10		(8.82)					
	3	15							
	4	15							
5. Old sellite wash tank (simulated by mixing liquid TNT and water)	1	10		26.0	22.7 (50.0)	None			
	2	10		(58.0)					
	3	10							
	4	15							
6. New nitrator 4 (batch process required)	1	10		73.0	14.2 (31.3)	8.5 (18.7)	10 min	77°C (170°F)	2318
	2	5							
	3	10							
	4	10							
7. New nitrator 5 (series 7 was only to be accomplished if shot 1 of series 6 did not detonate. This series was not done.)		No shots required		85.4 (188.0)	18.4 (40.5)	4.32 (9.5)	7 min	77°C (170°F)	2318
8. New nitrator 8 (simulated by mixing liquid TNT with nitrating acid)	1	10		80.4 (177.0)	22.7 (50.0)	None			
	2	15							
	3	15							
	4	15							

Table 17
General test procedures for small-scale tests

Preparation days

- cleanup test area from previous test
- repair support test equipment
- set up new test component on steel witness plate in field
- apply thermal insulation
- connect electrical leads
- connect water hose to heat transfer coils
- connect air line to pneumatic agitator motor
- inspect and grease pressure transducers
- prepare electronics
- remove premixed acid or wash solution from storage
- weight TNT and DNT for test

Test day

- start melting TNT and DNT (early in morning)
- start heating water for heat transfer and circulate through coils in vessel (early in morning)
- check electronics
- load movie camera (where appropriate)
- take still photographs of component on blast pad
- manually pour acid or wash solution into test vessel
- wait for acid or wash solution to heat above TNT melting temperature
- manually pour liquid TNT into tank and liquid DNT into DNT drop tank (where appropriate)
- agitate liquid TNT in acid or wash solution for on the order of 1 hr
- position booster and place initiators in booster
- clear area and alert instrumentation personnel of time before detonation
- energize DNT drop solenoid (for batch reactor tests)
- wait predetermined period for reaction; observe and control temperature in tank (for batch reactor tests)
- initiate detonation of booster
- wait for "all clear" from observer in control building
- wash down test area with water and sodium bicarbonate for tests resulting in nondetonation and acid spill.

Separator tests required a settling period prior to detonation. A portable agitator and heating coil assembly was used to heat the acid and agitate the TNT-acid mixture. At about 10 min prior to initiation, the portable assembly was manually removed from the separator box and buried in a nearby protective hole. During this period, the mixture settled separating into a liquid TNT layer floating on top of an acid layer. After the settling period, the C-4 explosive booster was initiated.

3.3 Procedures for Large-Scale Tests

The procedures for conducting the large-scale tests involving 90.8 kg (200 lb) of nitrobody per shot are outlined in table 18. Large-scale tests were planned for old nitrator 6, new nitrator 4, new nitrator 8, and the old acid wash tank. Due to operational problems only one large-scale nitrator 8 test was successfully completed. The large-scale tests were conducted at the NSTL facility near Bay Saint Louis, Mississippi.

Table 18
General test procedures for large-scale tests

Preparation day

- Clean area and prepare for test.
- Lay out steel witness plate.
- Place reactor on support, align and insulate.
- Place velocity probes into reactor.
- Connect all hose, insulate and bury all lines.
- Connect electrical lines for control and metering components, rpm indicator, velocity transducers (3), reactor thermocouples (2), agitator motor, heating tapes on reactor, velocity pipes and pipe extension for melt kettle solenoid, pump box and solenoids for heating/cooling cycle.
- Check all electrical line connections and bury.
- Position melt cart over reactor system and assure that any line entanglements are avoided. Provide quick disconnect socket connections for two melt mixers, two DNT drop-in solenoids, fuel pump to burner, water pump to steam generator and two thermocouples. Tension from winch system will disconnect the above lines to assure no entanglement during remote cart operation.
- Connect steam lines to kettles.
- Insulate steam kettles and protect reactor tank and bottles from weather elements.
- Do not place pump-box and solenoids into ground. Protect from weather and place on high ground.
- Check propane gas supply.
- Check water supply in flash tank and fuel supply for the steam generator; refill if needed.
- Position TV camera for wide-angle view of reactor and cart.
- Position flexible hose feed lines from melt kettle above the reactor openings so that no obstacles develop during remote cart operation.
- Provide sheet metal for making funnel between flexible hose feed line and reactor opening.
- Install floating flag and pole indicator to melt kettles to alert control of any solenoid malfunction during the TNT/DNT dump cycle. Device to be in TV camera range.
- Photograph test shot and label test appropriately.

Test Day

- Check electronics and control equipment.
- Fill hot and cold water reservoirs and all hose lines (heat/cool solenoid switching necessary).
- Start up propane gas burners and hot water circulation system (early in morning).
- Pour acid contents into reactor; agitate contents.
- Hook up indicator for power to reactor motor and check (sound pick-up or volt meter).
- Load movie camera (where appropriate).
- Check TV camera for optimum visual coverage.
- Photograph the reactor system on the blast pad.
- Place pump box and solenoids into ground and cover.
- Measure appropriate amounts of DNT and/or TNT explosive into each melt kettle.
- Final check before remote mode begins.
- Position booster and place initiators in booster.
- Begin TNT/DNT steam cycle for melt kettles.
- Clear area.
- Turn on external heating tapes on reactor if any. Watch for any high temperature gradients.
- Adjust reactor agitator speed to select rpm.
- Begin slow agitation of TNT/DNT in melt kettle (after 1/2-hour into melt).
- Maintain proper test temperature in reactor by switching to appropriate heating/cooling cycle.
- Wait for completion of melt; observe thermocouple reading (approximately 3 hr melt cycle).
- Shut down fuel supply to steam generator.
- Turn on heating tape surrounding drop-in pipe (freeze prevention).
- If heating tapes are necessary to alleviate any freeze-up of the melt kettle feed pipe extension and if sufficient time was allowed for warm-up, turn off the heating tape and provide an adequate cooling period for any hot spots that may occur. Similarly, turn off the external reactor heating tapes (if used) prior to actuation of the TNT/DNT dump cycle.
- Dump TNT into reactor and adjust agitator speed.
- Allow completion for a 50 min TNT mixing cycle in reactor and then begin 10 min countdown.
- Dump DNT into reactor (nitrator 4 only).
- If solenoid problems occur during drop-in condition begin contingency plan.
- Begin withdrawal of melt cart 2-1/2 min into countdown (command from control; if mechanical problems occur, start contingency plan).
- Watch TV monitor for proper functioning of carriage withdrawal.
- Announce countdown at 5 min.
- Adjust for final temperature and agitator speed.
- Announce countdown at the 3, 2 and 1 min periods.
- Prepare firing circuit.
- Final countdown of last 30 sec proceeds at 1 sec intervals.
- Fire (for no-fire condition - start contingency plan).
- Wait 2 min before initial posttest observation; check TV monitor to assure safe entrance.
- Wear protective clothing during posttest handling near ground zero.
- Clean-up operation begins; utilize sodium bicarbonate and water to neutralize acid residuals, if any.
- Playback signal acquisition and provide records (pressure/impulse, temperature, rpm, velocity).

4. TEST RESULTS

This section contains the results for each series of tests which were completed. Peak overpressure and scaled positive impulse versus scaled distance have been computed from raw data for each test. The instrumentation used to obtain these data is described in section 2 and appendix A. The method used to reduce the data is discussed in appendix B.

4.1 General Description of Data Presented

As the data are presented, it will be shown that the three or four shots within a series generally represent different levels of intensity on the transition between a low order reaction and a full detonation. For this reason, the shot with the highest airblast output will be most representative of a detonation in a full-scale system. The data do not represent a scatter about some average curve; therefore, a curve fit to all the data points in a series would be meaningless.

In this work, TNT equivalency is computed based on an upper envelope fit to the experimental data. This upper envelope curve is drawn on each figure showing peak overpressure and scaled positive impulse. In many cases, some data points fall above the curve which is drawn. These data points either represent data scatter about an average curve fit to the highest output shot in the series, or they represent recorded data points which clearly do not follow the trend set by the other data but which could not be eliminated due to an obvious instrumentation or interpretation error. Based on these upper envelope curves, TNT equivalency versus scaled distance has been computed and is presented in this section.

Detonation velocity was investigated in each test using fiber optic probes and ion probes in the small-scale shots, and using continuous probes, ion probes, and a pressure sensitive switch in the large-scale tests. The detonation (or more properly reaction front) velocity data are presented and discussed in appendix C. A summary of the average velocities found for each test is presented with the data given for each test series.

4.2 Test Results for Series 1 (old nitrator 3A)

Old nitrator 3A contains DNT and required a batch process to simulate the proper chemical mixtures in the field. In spite of some operational problems with the batch reaction and DNT dump, all four shots produced very similar results. Peak overpressure is plotted in figure 33 for the series. Shot 2 produced the highest pressure at most locations and therefore strongly influenced the selection of the upper envelope curve.

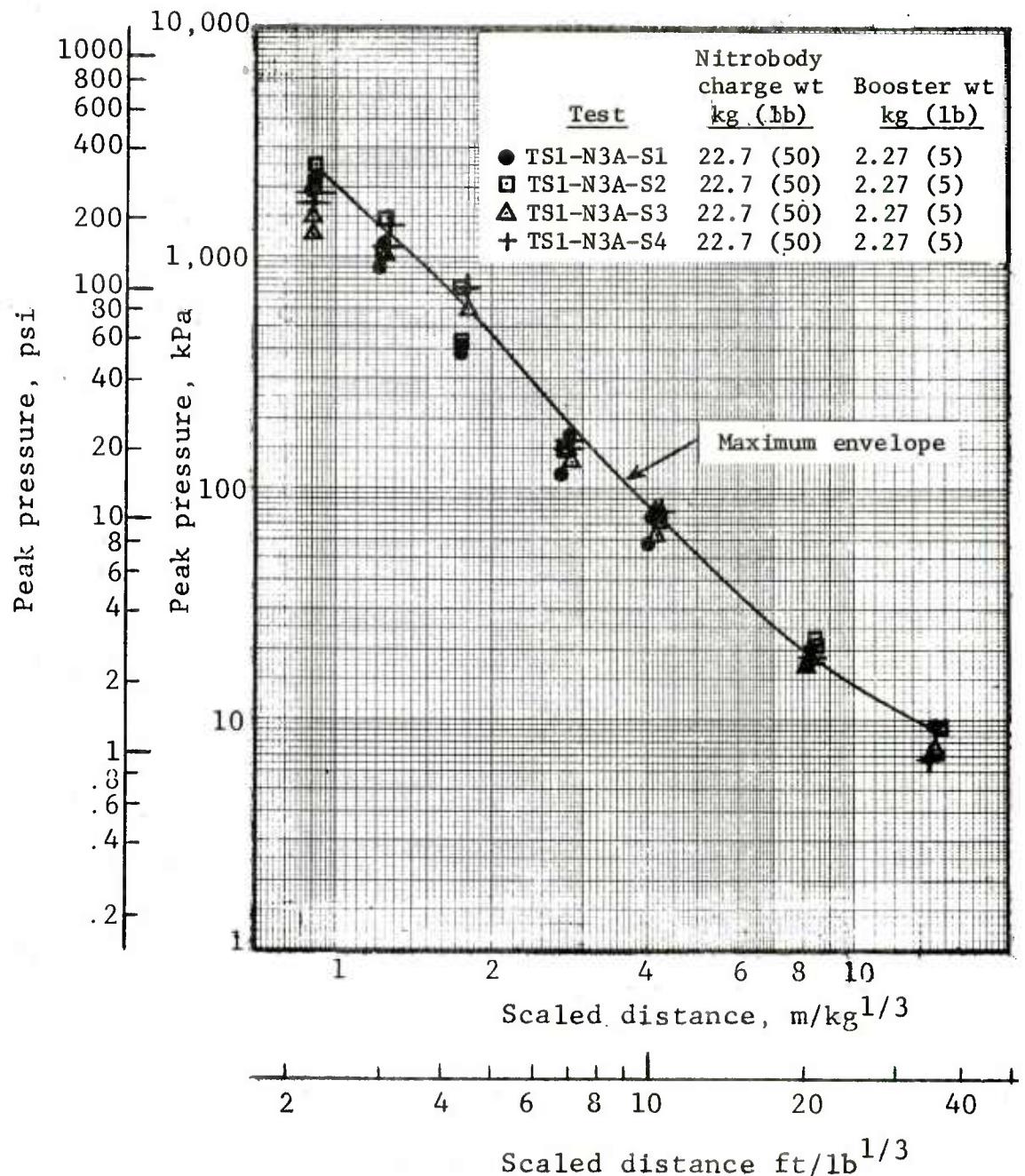
Scaled positive impulse is presented in figure 34. In this case, a smooth curve fit the maximum readings at each location and the upper envelope actually represents the maximum values obtained. This plot shows a phenomenon noticed frequently in the tests. The scaled impulse data tend to have increased scatter as scaled distance decreases below some value (in this case about $2.7 \text{ m/kg}^{1/3}$ or $7 \text{ ft/lb}^{1/3}$). This scatter could be attributable to near field geometric effects, near field shock instability, or increased instrumentation error for the first three gages.

Percent TNT equivalencies for peak overpressure and scaled positive impulse are plotted in figure 35. These represent the maximum envelopes in figures 33 and 34 respectively. Impulse equivalency should be most representative of energy stored in the blast field compared to the blast field produced by a TNT hemisphere detonated on the ground. These data indicate that between 1.6 and perhaps 2 times the energy of an amount of pure TNT equal to the weight of the nitrobody in the tank is released.

The reaction front velocity data for this series of tests (table 19) were inconclusive. Only the initial shot provided readable data. The average velocity was found to be 4722 m/sec (15,488 fps) which seems to be somewhat low when compared to data from test series 2, 3 and 6. Either the data are not accurate or the detonation front did not achieve its maximum value within the length of the reactor.

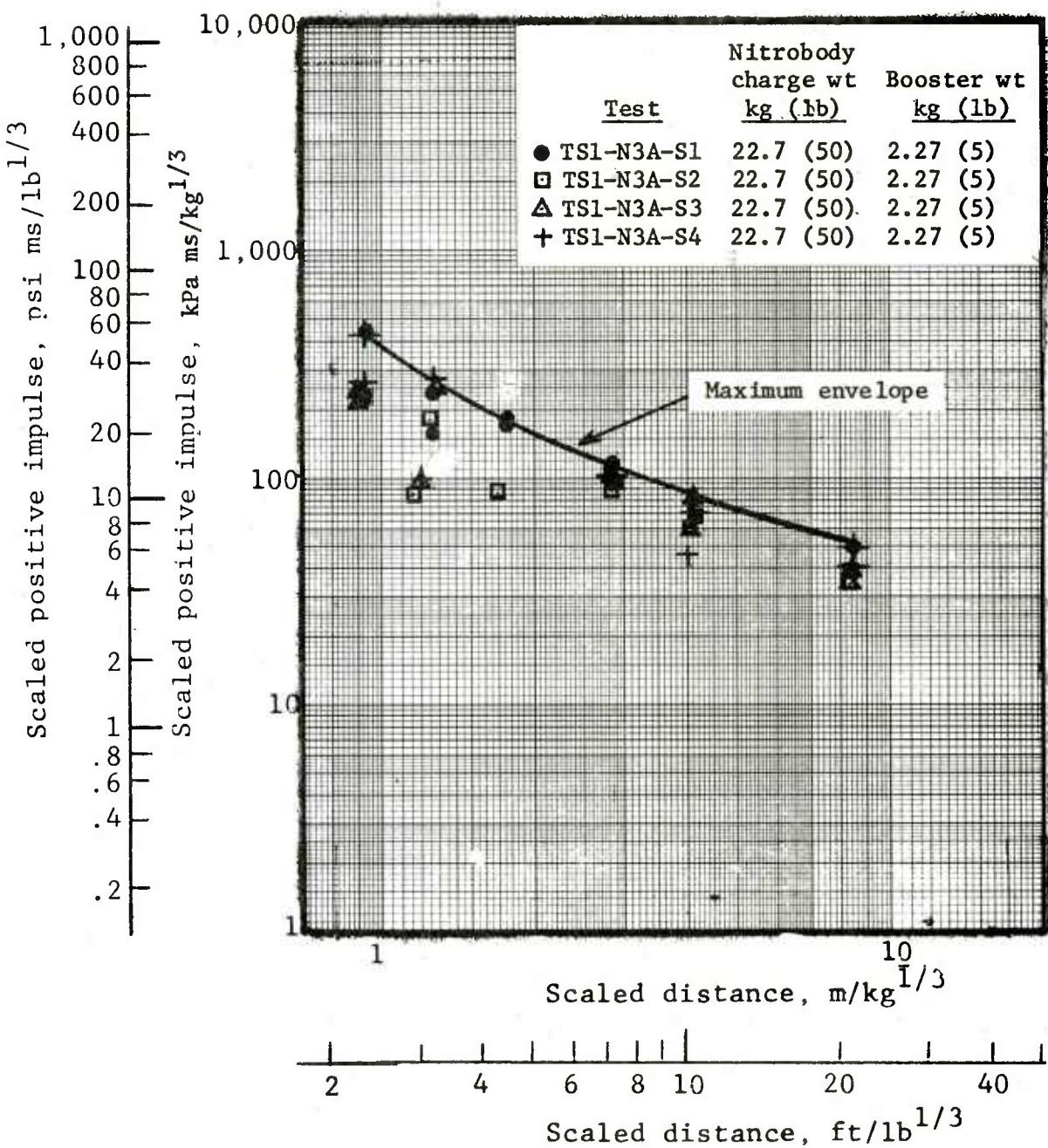
4.3 Test Results for Series 2 (old nitrator 6)

The chemical composition of old nitrator 6 was simulated in the field using an agitated mixture of liquid TNT and nitrating acid. The general philosophy taken on each shot was to agitate the mixture for as long as practical prior to detonation in order to assure that a portion of the TNT became dissolved in the acid, as exists in the continuous process. This mixing time varied from 20 min to 2 hr depending on weather conditions and/or operational problems.



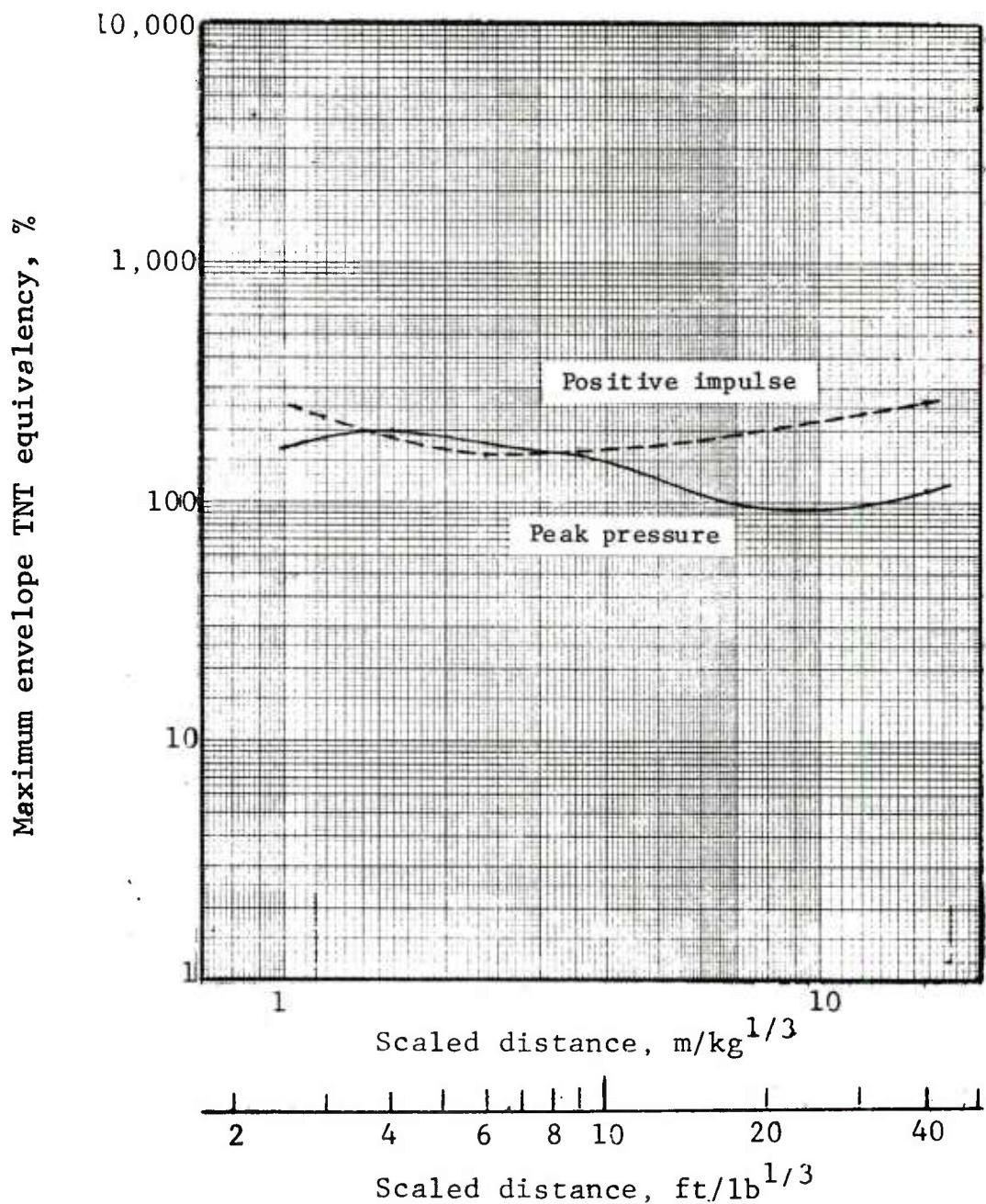
Test series 1

Fig 33 Peak pressure, old nitrator 3A configuration, 22.7 kg (50 lb) nitrobody content



Test series 1

Fig 34 Scaled positive impulse, old nitrator 3A configuration, 22.7 kg (50 lb) nitrobody content



Test series 1

Fig 35 TNT equivalency, old nitrator 3A configuration, 22.7 kg (50 lb) nitrobody content

Table 19

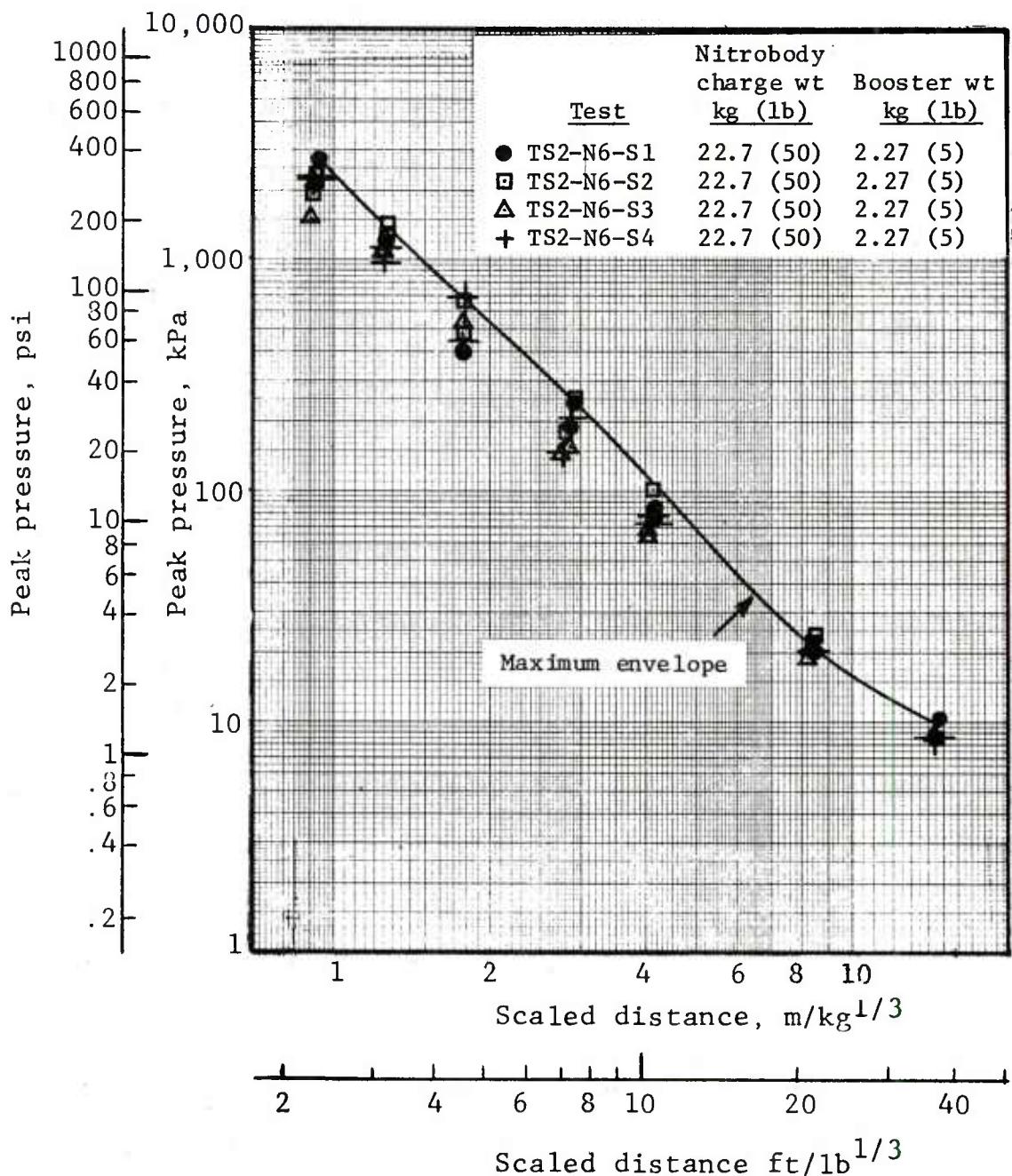
Average reaction front velocities for nitrator 3A

<u>Shot</u>	Average reaction front velocity m/sec (fps)	Booster weight (% nitrobody present)	Special considerations
1	4722 * (15,488)	10	Detonation occurred
2		10	Detonation occurred
3		10	Detonation occurred
4		10	Detonation occurred

* Average included data from probe located in booster.

Even with a mixing time as short as 20 min, the dissolved TNT should have approximated the real system quite adequately. This is supported by the good correlation of peak overpressure data in figure 36 and scaled positive impulse data in figure 37. In figure 36, peak overpressure could be ordered (one curve lying above another) with shot 2 highest, shot 1 next, shot 4 next and shot 3 lowest. This ordering does not correlate with the TNT-acid mixing duration, so it can be assumed that above 20 min, mixing duration has a negligible influence on output.

TNT equivalency is plotted in figure 38. Impulse equivalency is near or above 200 percent indicating that about twice the blast energy of a TNT hemisphere at ground level at the nitrobody weight is released in a nitrator 6 detonation. Detonation velocity for the nitrator 6 series is summarized in table 20. The values ranged from 4669 m/sec (14,986 fps) to 6758 m/sec (22,166 fps) in the tests. This range is indicative of a high order detonation in all cases. It is interesting that the detonation velocity ordering corresponds to the blast output ordering, although this could be coincidental. The ordering of blast output and perhaps detonation velocity is indicative of a transition from weak detonation to strong detonation.



Test series 2

Fig 36 Peak pressure, old nitrator 6 configuration, 22.7 kg (50 lb) nitrobody content

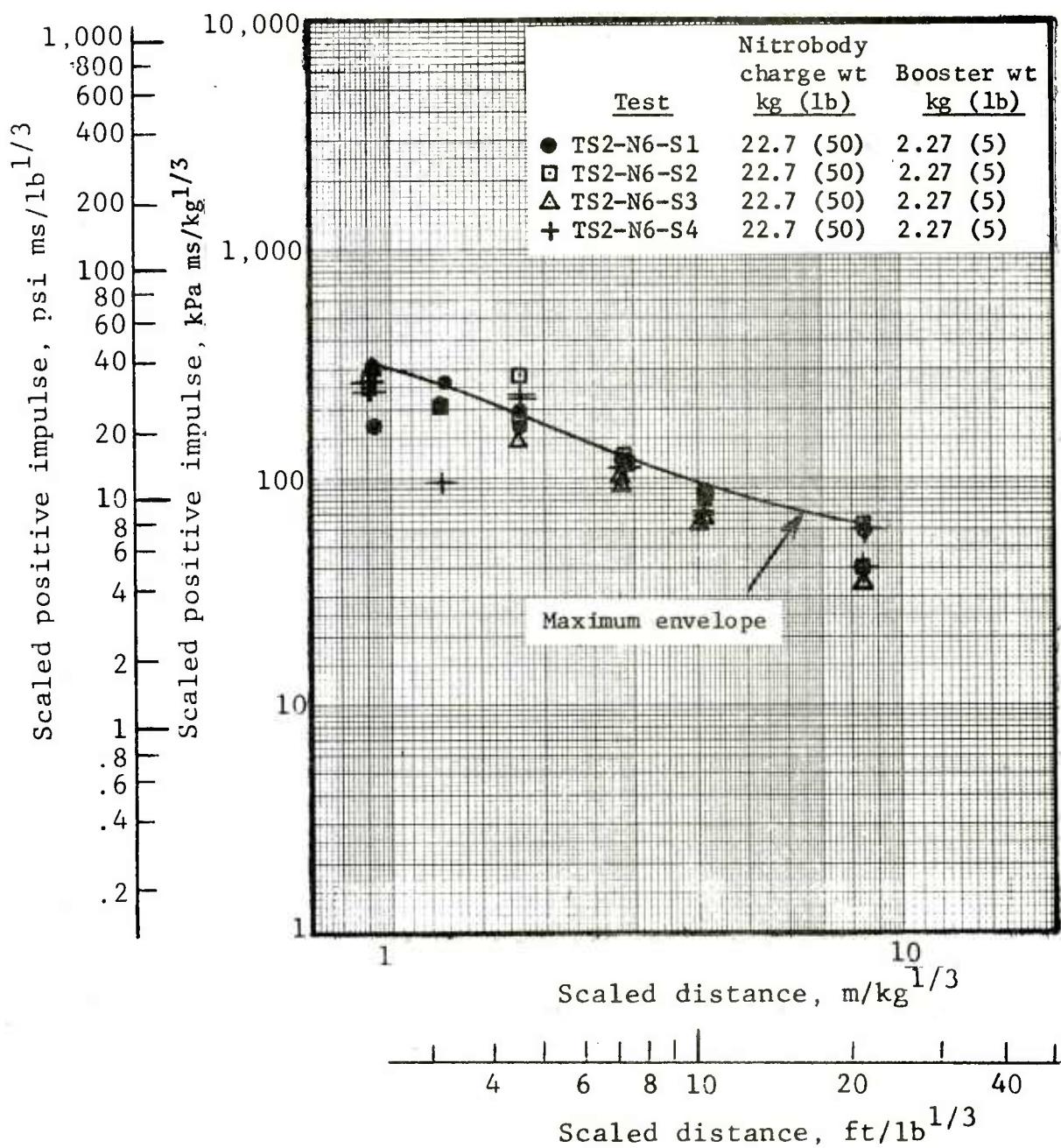
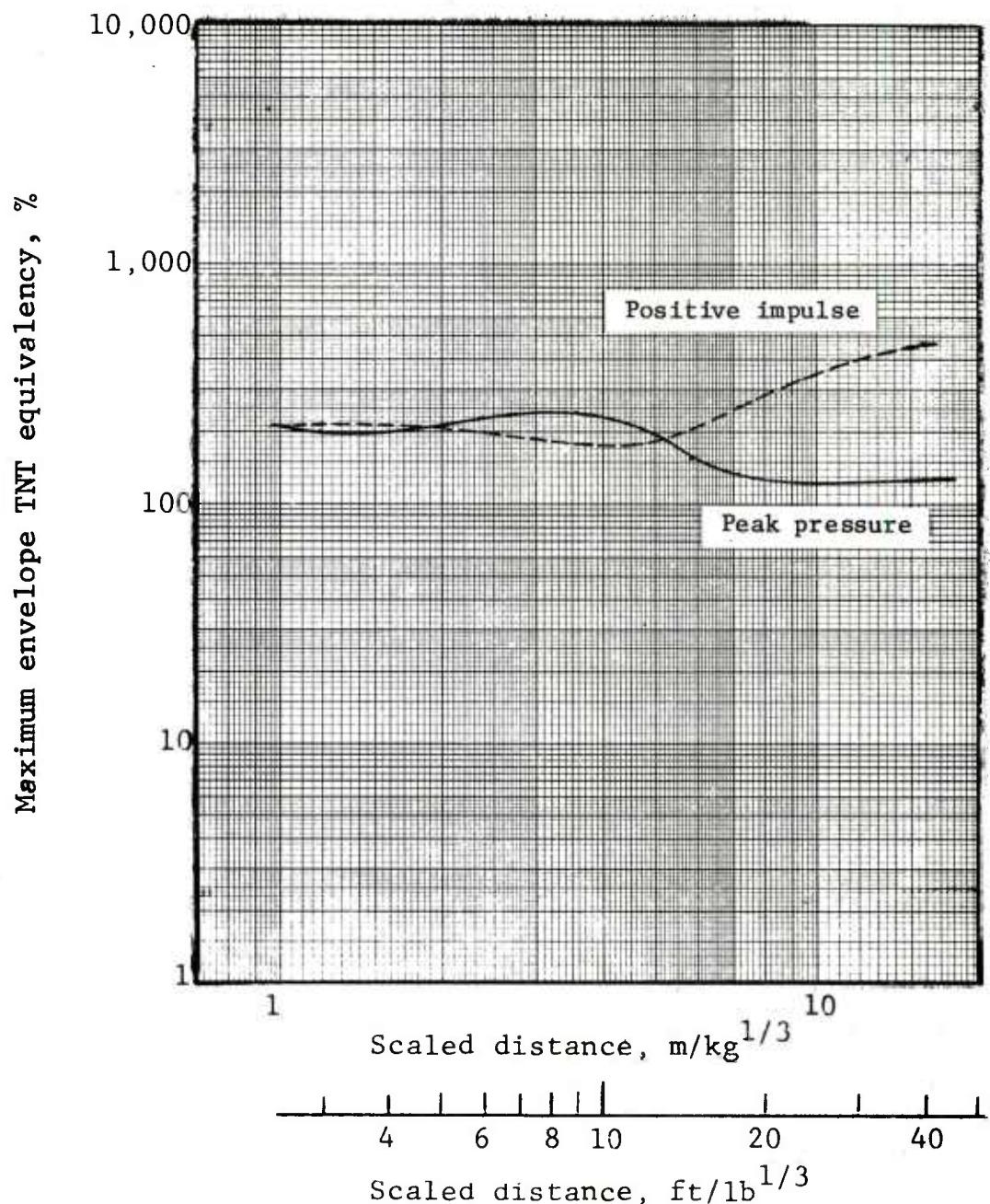


Fig 37 Scaled positive impulse, old nitrator 6 configuration, 22.7 kg (50 lb) nitrobody content



Test series 2

Fig 38 TNT equivalency, old nitrator 6 configuration, 22.7 kg (50 lb) nitrobody content

Table 20

Average reaction front velocities for nitrator 6

<u>Shot</u>	<u>Average reaction front velocity m/sec (fps)</u>	<u>Booster weight (% nitrobody present)</u>	<u>Special considerations</u>
1		10	Detonation occurred
2	6758 (22,166)	10	Detonation occurred
3	4569 * (14,986)	10	Detonation occurred
4	6132 * (20,113)	10	Detonation occurred

* Average included data from probe located in booster.

4.4 Test Results for Series 3 (old separator 6)

Gravity separator 6 was simulated using a rectangular box. The first shot of the series was hand mixed for a short time and allowed to settle for 5 min prior to detonation with a 5 percent (percent of the nitrobody weight) C-4 booster in contact with the ends of the rectangular tank at the level of the liquid TNT layer. This shot did not detonate, probably because of the small booster size.

Shot 2 was agitated with a pneumatic air mixer at high speed for 20 min. The mixture was allowed to settle for 15 min prior to detonation. A 10 percent C-4 booster was used in this shot, but detonation was not achieved.

In the third shot, mixing was maintained for 50 min and settling for 10 min. A 10 percent booster in good contact with the end of the tank at the TNT level was used. Much to our surprise (after the first two tests) an intense detonation occurred. No tank components were found; the witness plate was punched through outlining the tank; and a very large crater was found. The difference between this shot and shot 2 could have been the mixing duration, settling time, or booster contact. The most likely explanation for the dramatic difference in test results was believed to be poor booster contact on shot 2.

In the final separator shot, an attempt was made to reproduce the previous shot as accurately as possible. The mixing duration was 1 hr and settling time was 15.5 min. The most intense output and largest crater for the series were obtained with this shot. Since the settling time for this shot was nearly the same as for shot 2, settling time apparently was not a major influence on sensitivity. The minor differences in results from shots 3 and 4 are probably attributable to a combination of exact booster placement, mixing duration, and settling time.

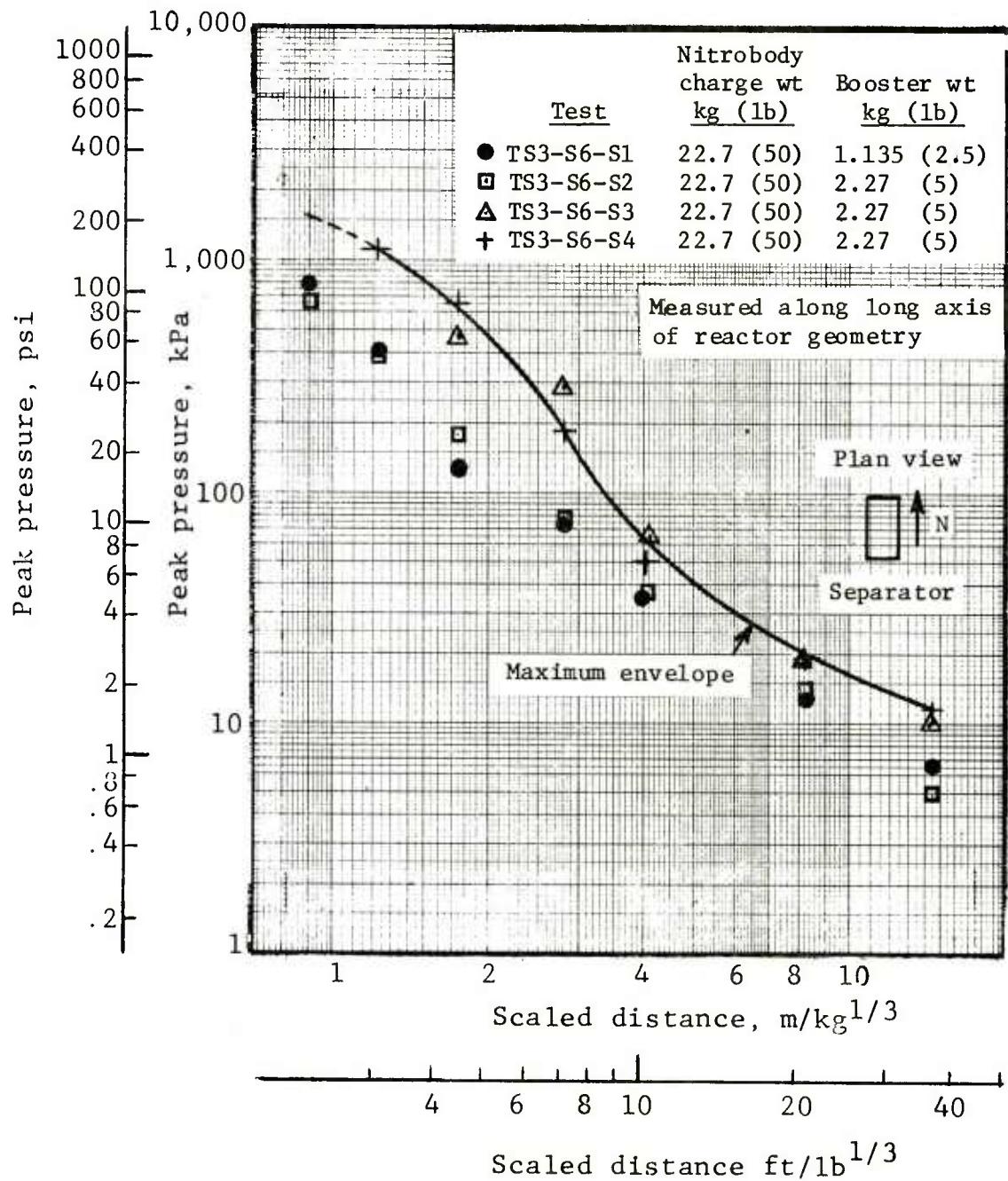
Figure 39 shows peak overpressure versus scaled distance along the north blast pad. The north pad is on the long axis of the separator box. Shots 1 and 2 did not detonate and lie together well below shots 3 and 4 which did detonate. Scaled positive impulse is presented in figure 40 for the north blast pad. Pressure and impulse TNT equivalencies are plotted in figure 41 for the north leg of the blast pad.

In figures 42, 43 and 44 peak overpressure, scaled positive impulse and TNT equivalency percents are plotted versus scaled distance for the east leg of the blast pad. By comparing the TNT equivalency curves in figures 41 and 44 for the two directions, it can be seen that pressure is higher close to the source along the east leg and impulse along the north leg is higher in the near field. These observations were expected based on the configuration. In the two directions, the impulse equivalencies converge fairly well to 150 to 250 percent beyond a scaled distance of about $2 \text{ m/kg}^{1/3}$ ($5 \text{ ft/lb}^{1/3}$). Pressure equivalency along the north leg follows this same trend but diverges significantly from the other equivalency curves along the east leg.

Reaction front velocity data are summarized in table 21 for the separators. These data correlate quite well with the ordering of blast output and crater sizes obtained. The intensity of the output increased in order from shot 1 to shot 4 and reaction front velocity increased in this same order.

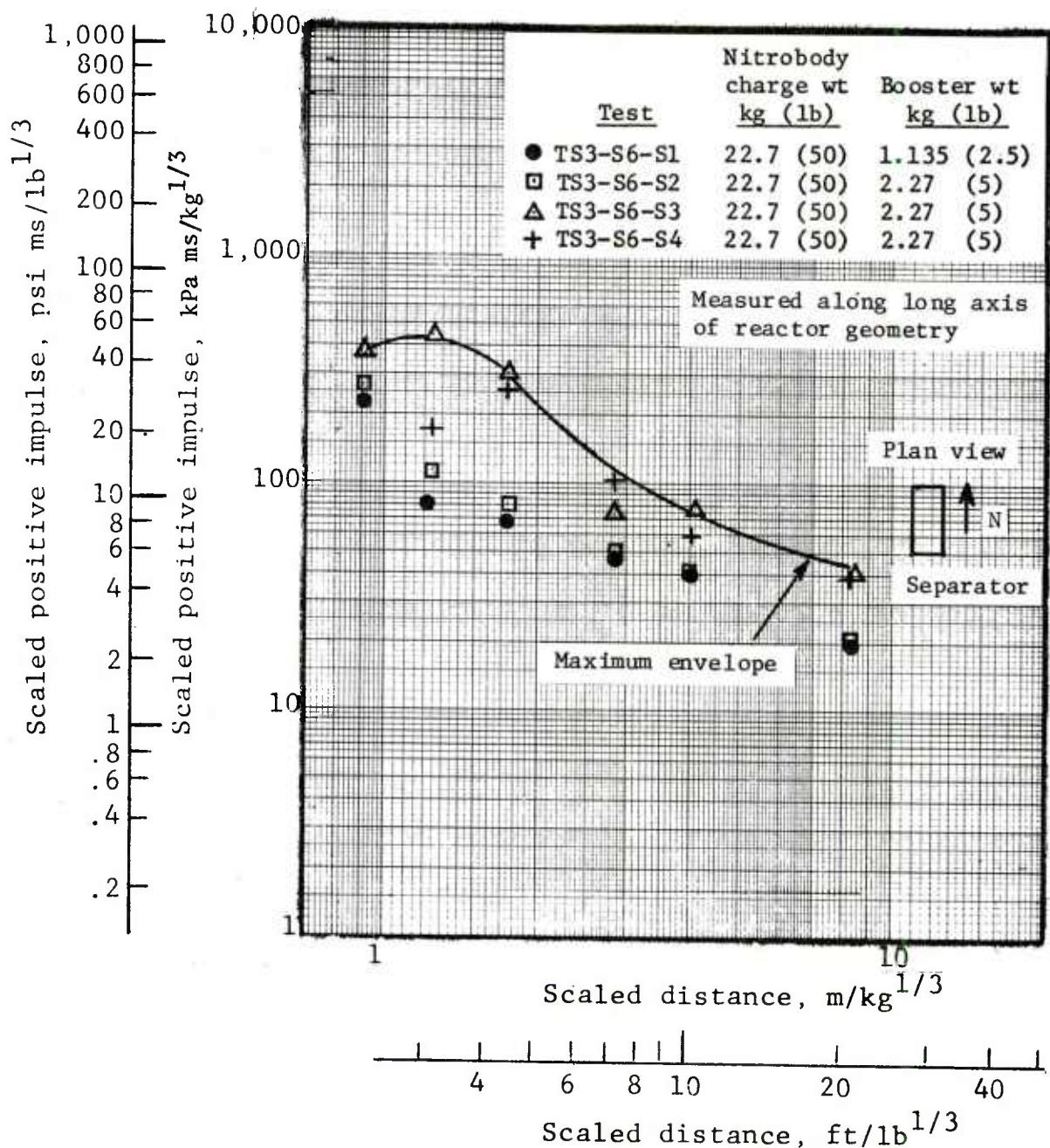
4.5 Test Results for Series 4 (old acid wash tank compartment)

The acid wash tank series was designed to simulate the inlet mixing compartment of the ten-compartment acid wash tank (five mixing chambers and five gravity separators). The complete system was considered to be much too complex to simulate in this TNT equivalency test program. Therefore, the one compartment was selected to be representative.



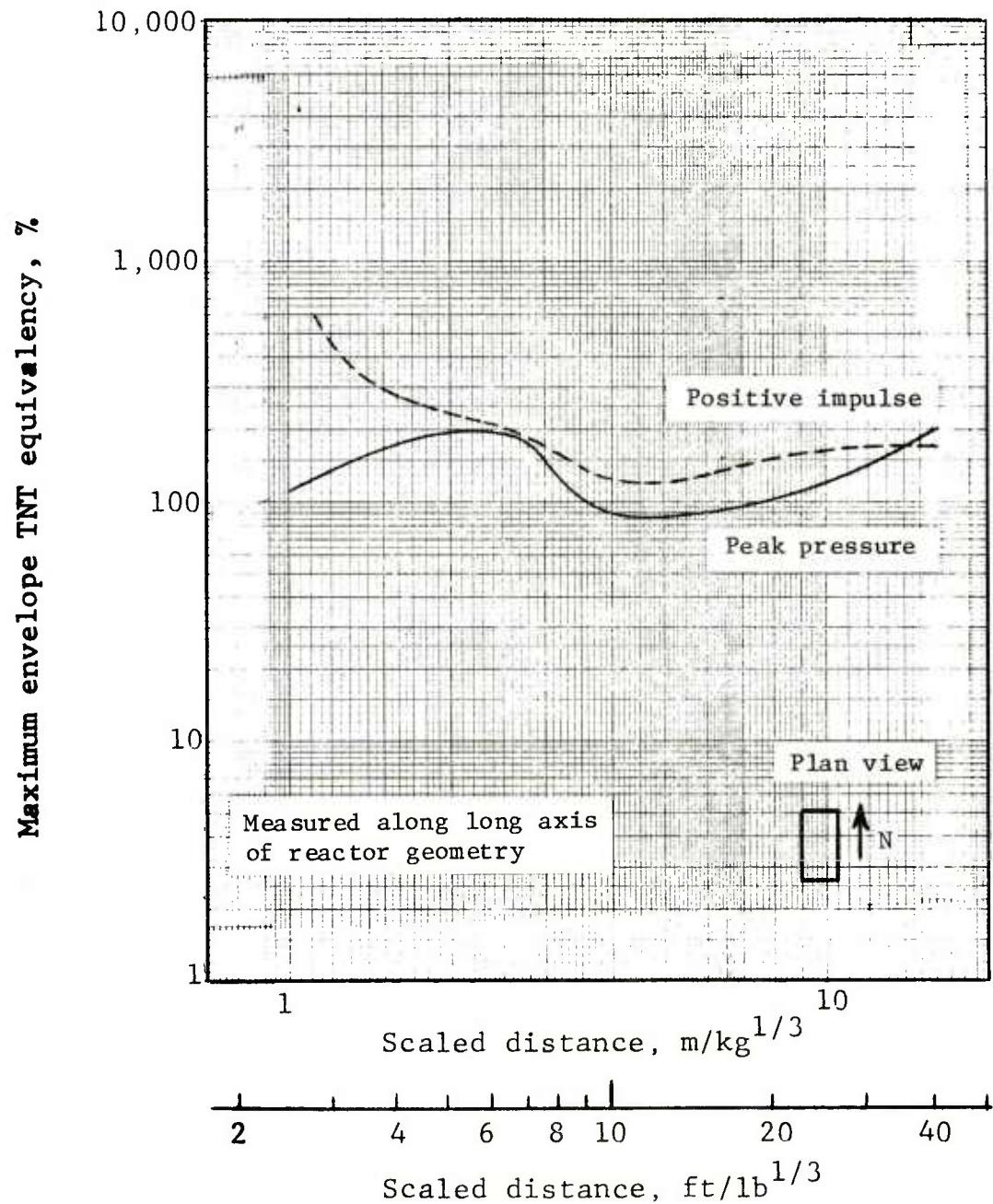
Test series 3

Fig 39 Peak pressure, separator 6 (north leg) configuration, 22.7 kg (50 lb) nitrobody content



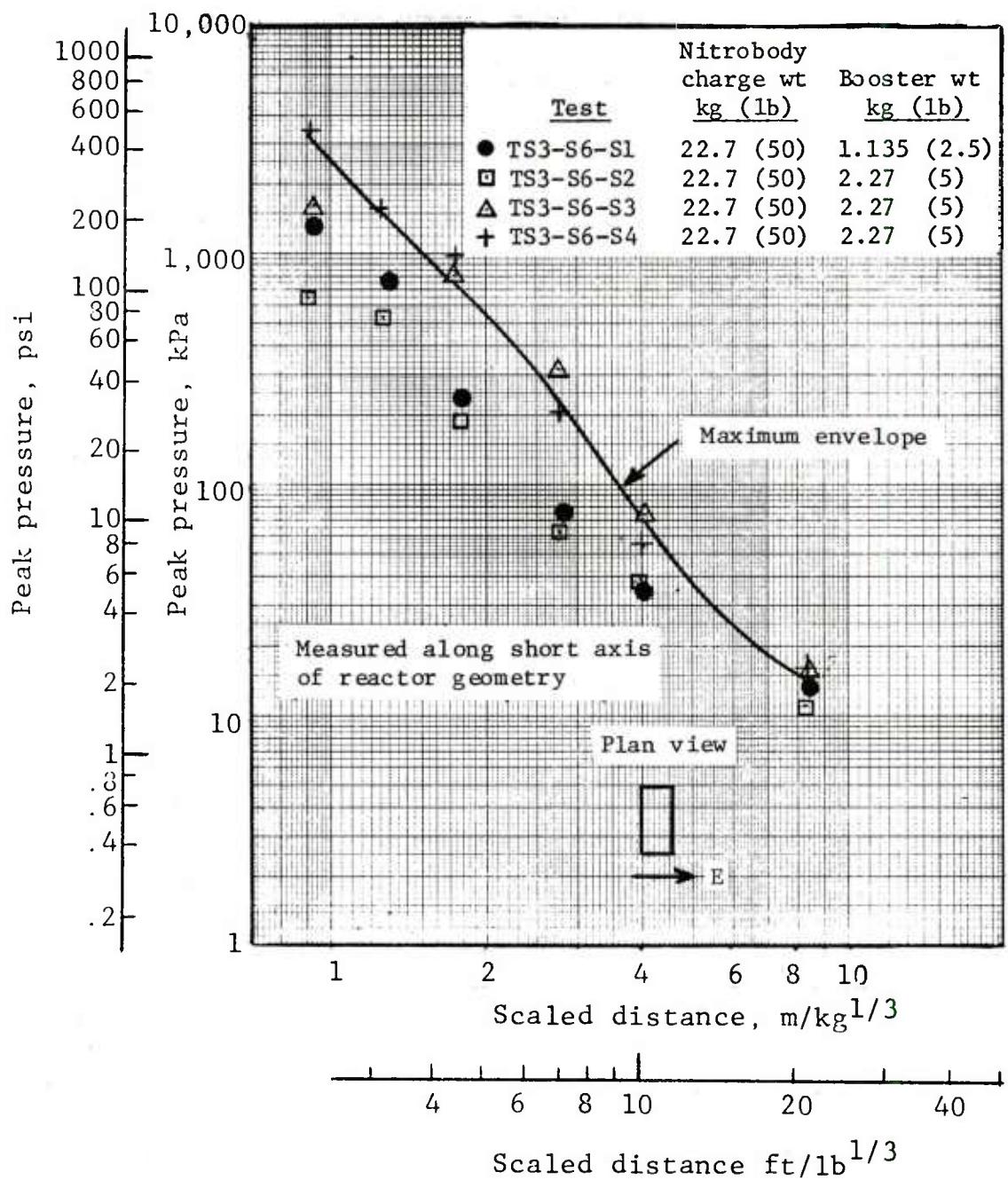
Test series 3

Fig 40 Scaled positive impulse, separator 6 (north leg) configuration, 22.7 kg (50 lb) nitrobody content



Test series 3

Fig 41 TNT equivalency, separator 6 (north leg) configuration, 22.7 kg (50 lb) nitrobody content



Test series 3

Fig 42 Peak pressure, separator 6 (east leg) configuration, 22.7 kg (50 lb) nitrobody content

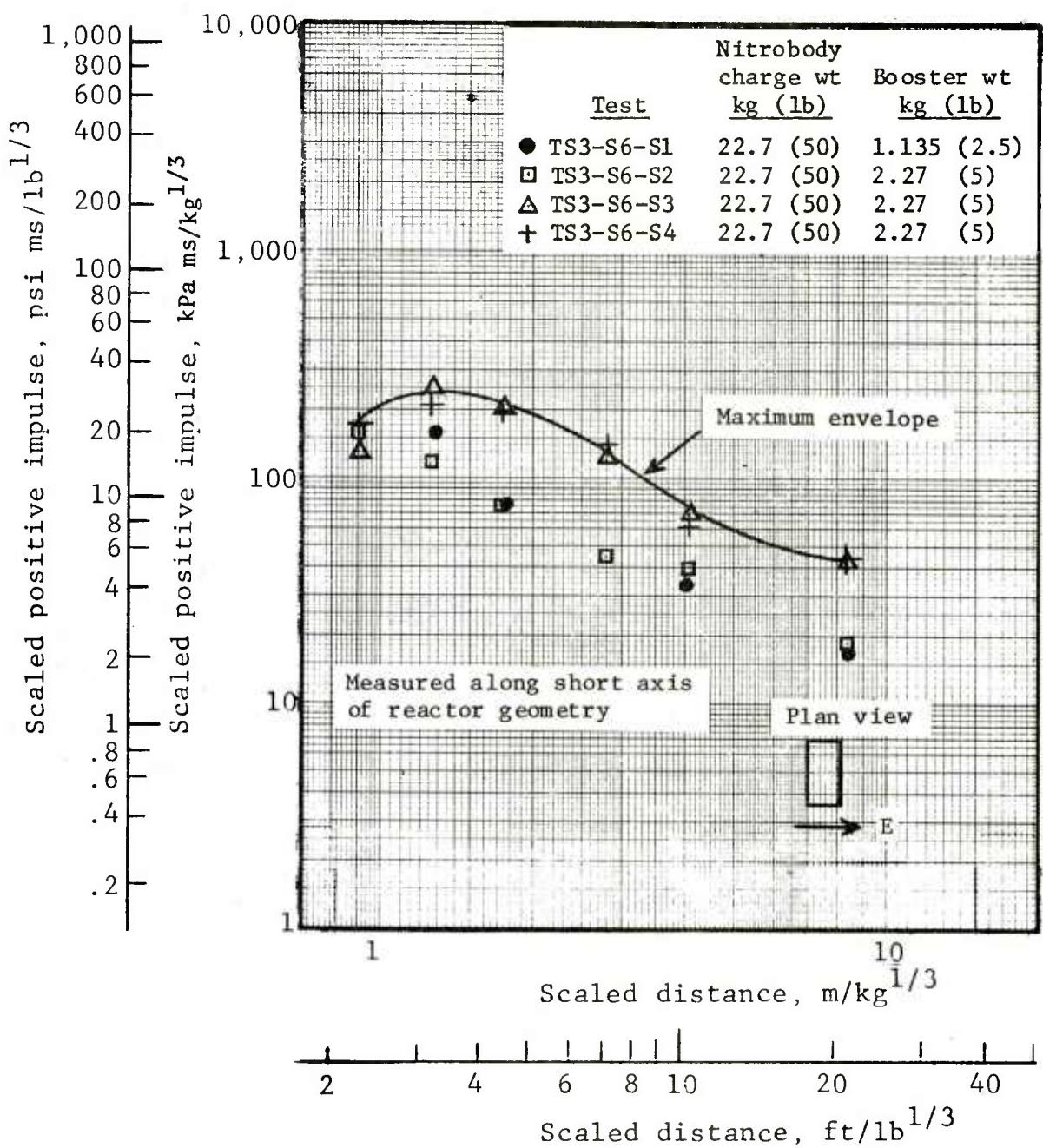
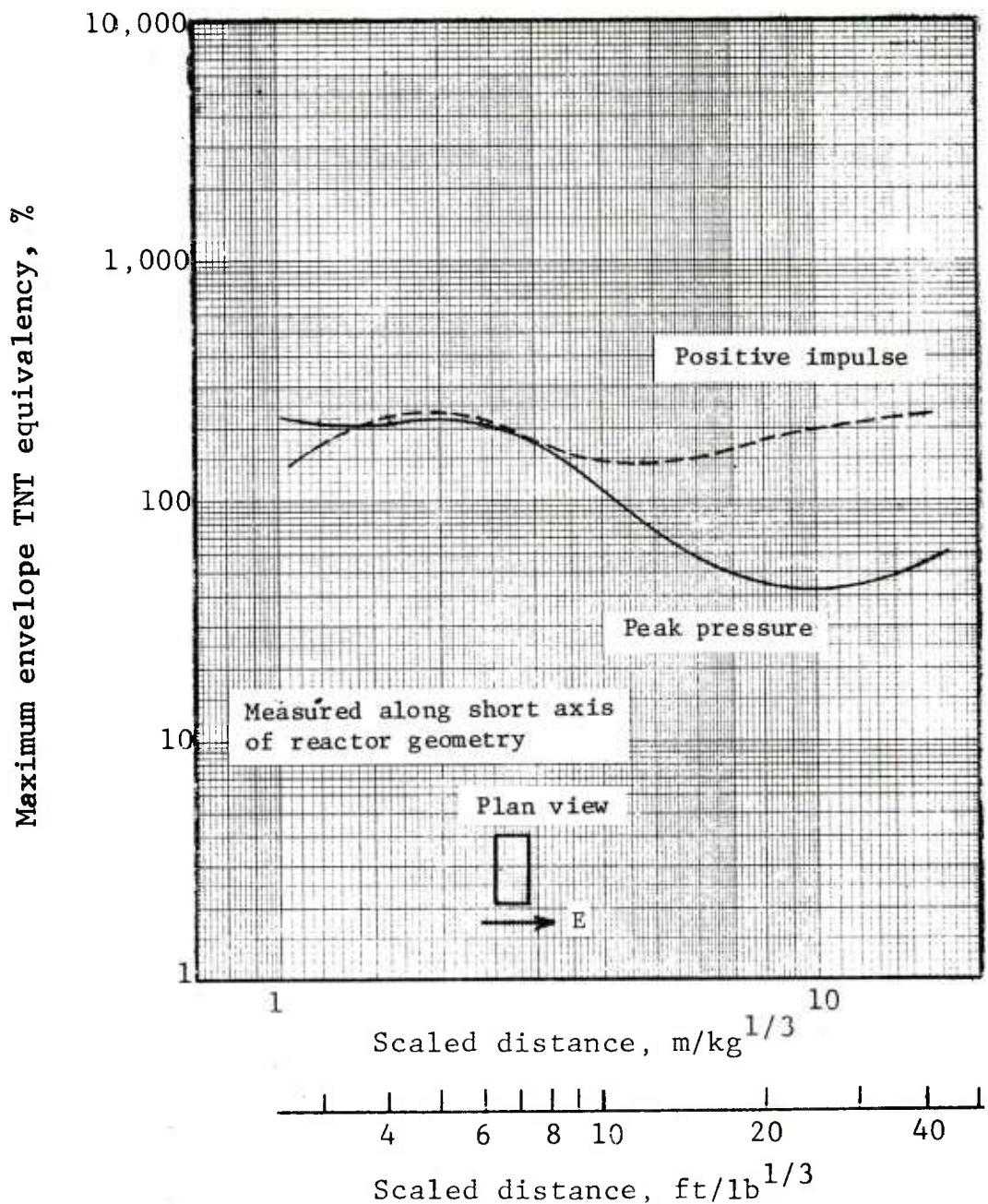


Fig 43 Scaled positive impulse, separator 6 (east leg) configuration, 22.7 kg (50 lb) nitrobody content



Test series 3

Fig 44 TNT equivalency, separator 6 (east leg) configuration, 22.7 kg (50 lb) nitrobody content

Table 21

Average reaction front velocities for separator 6
(measured along axis in north-south direction)

<u>Shot</u>	Average reaction front velocity m/sec (fps)		Booster weight (% nitrobody present)	Special considerations
1	1022	(3352)	5	Apparently did not detonate
2	2261 *	(7416)	10	Apparently did not detonate
3	5997	(19,670)	10	Full detonation
4	7082	(23,229)	10	Full detonation (largest crater size observed for small-scale series)

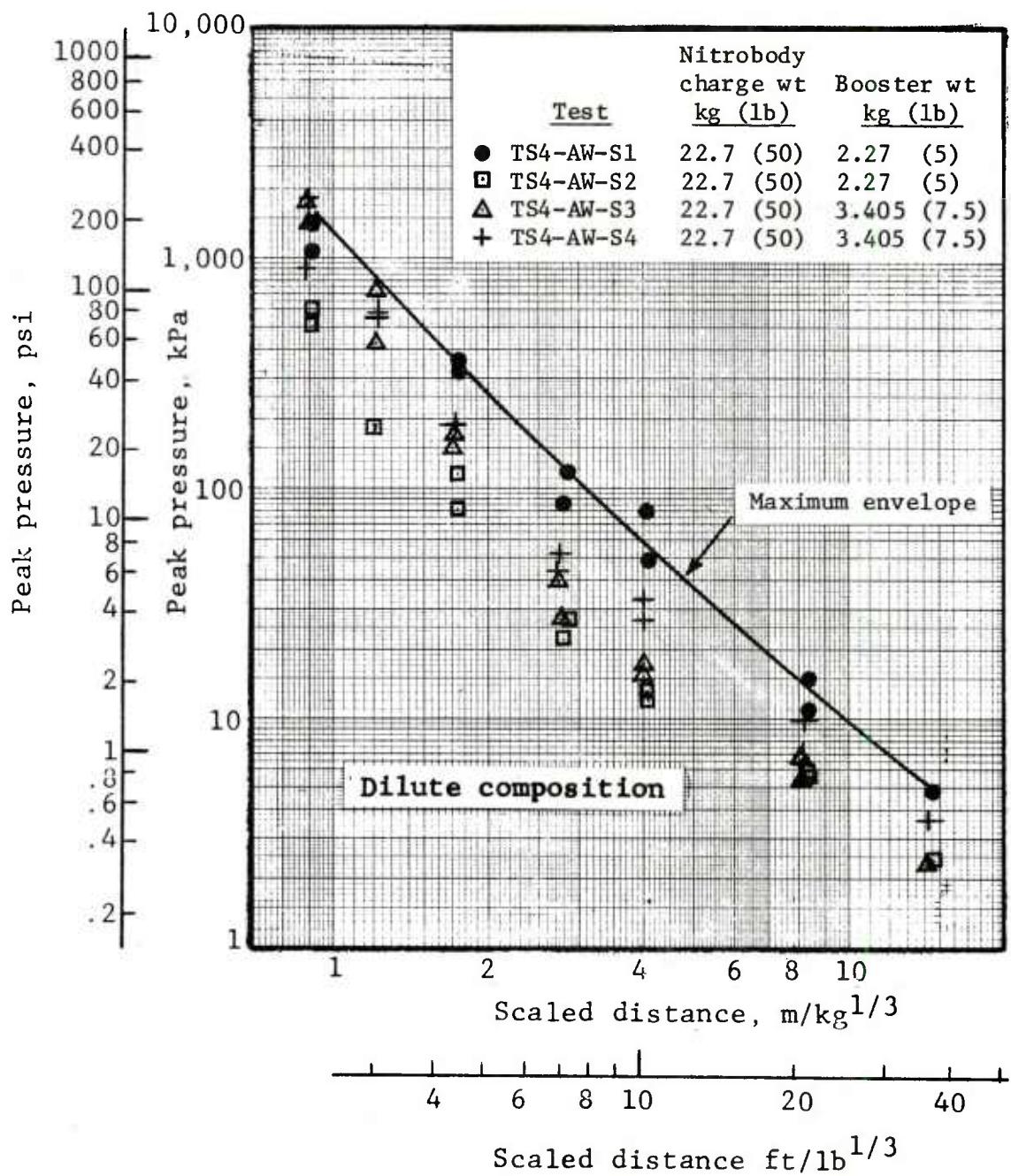
* Average included data from probe located in booster.

Unfortunately, the chemical composition in these tests inadvertently was much too dilute. The real system contains 85 weight percent of liquid TNT whereas the test composition contained only 53 weight percent TNT. The results for the dilute mixture are shown in figures 45 and 46. Two large-scale acid wash tank shots were to be conducted to experimentally determine the acid wash tank output, but operational problems with the large-scale test program prohibited completion of these tests.

TNT equivalency curves for the dilute acid wash tank series are presented in figure 47. Impulse equivalency in these tests varied between 60 and 130 percent..

Detonation velocity from the acid wash tank series is summarized in table 22. Only shot 2 produced readable data. The value from shot 2 appears to be quite high when compared to the observed damage and blast output. Therefore, these data are considered to be questionable.

In section 5, the peak overpressure and scaled positive impulse data from all the available tests are correlated quite well and used to predict the expected real acid wash tank compartment blast output with good reliability. See figures 66, 67 and 68 in section 5 for the results.



Test series 4

Fig 45 Peak pressure, acid washer configuration, 22.7 kg (50 lb) nitrobody content

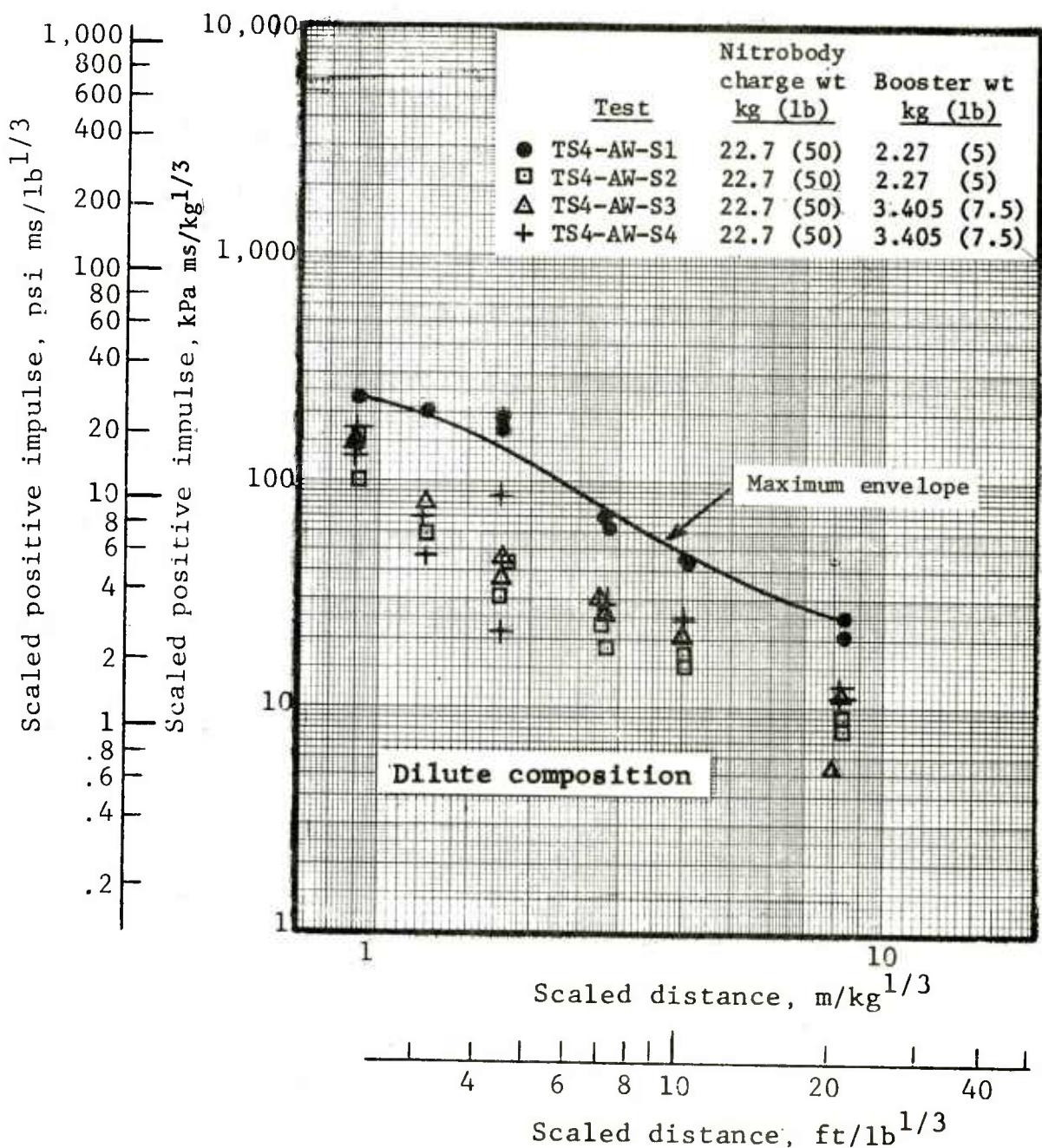
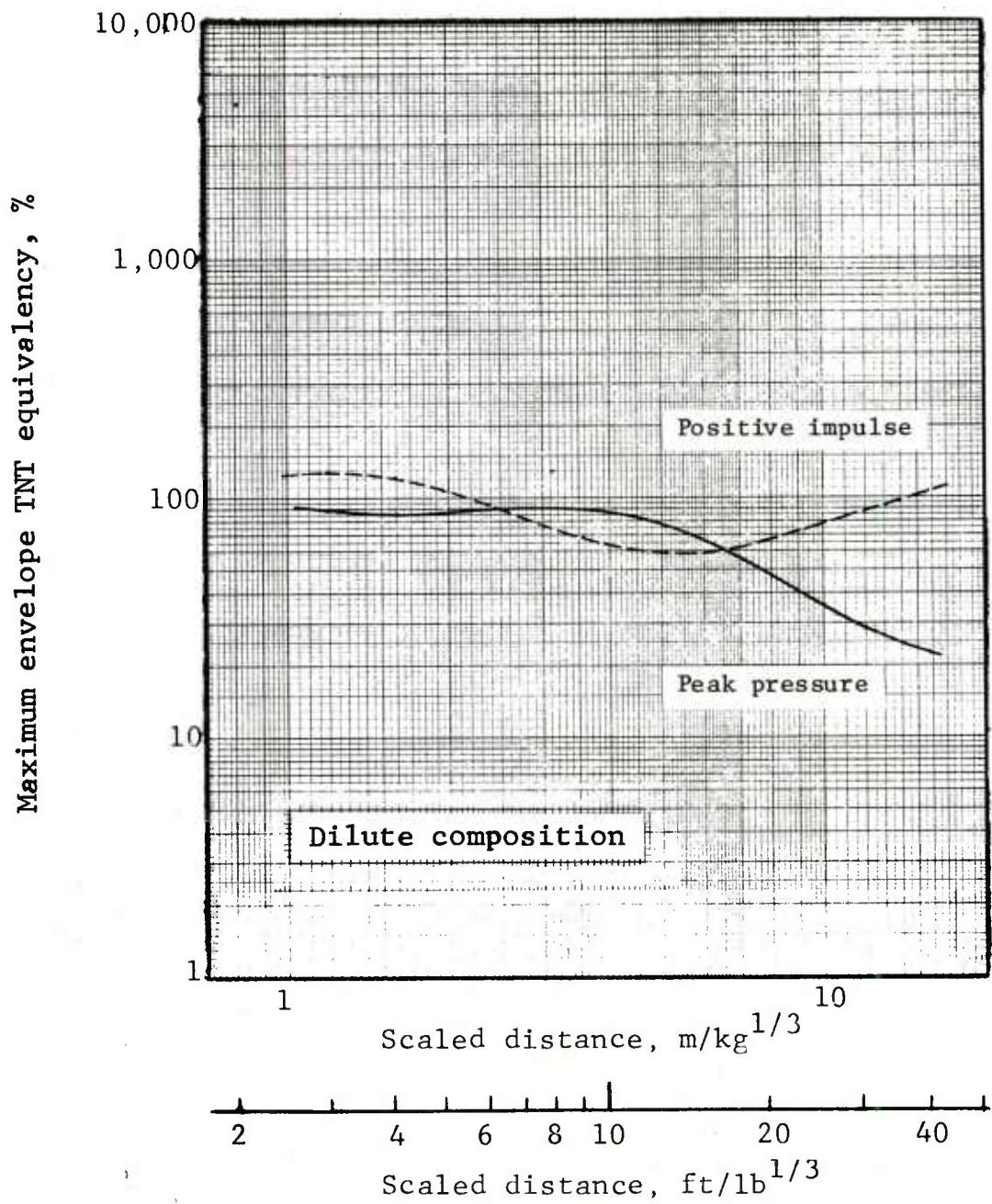


Fig 46 Scaled positive impulse, acid washer configuration, 22.7 kg (50 lb) nitrobody content



Test series 4

Fig 47 TNT equivalency, acid washer configuration,
22.7 kg (50 lb) nitrobody content

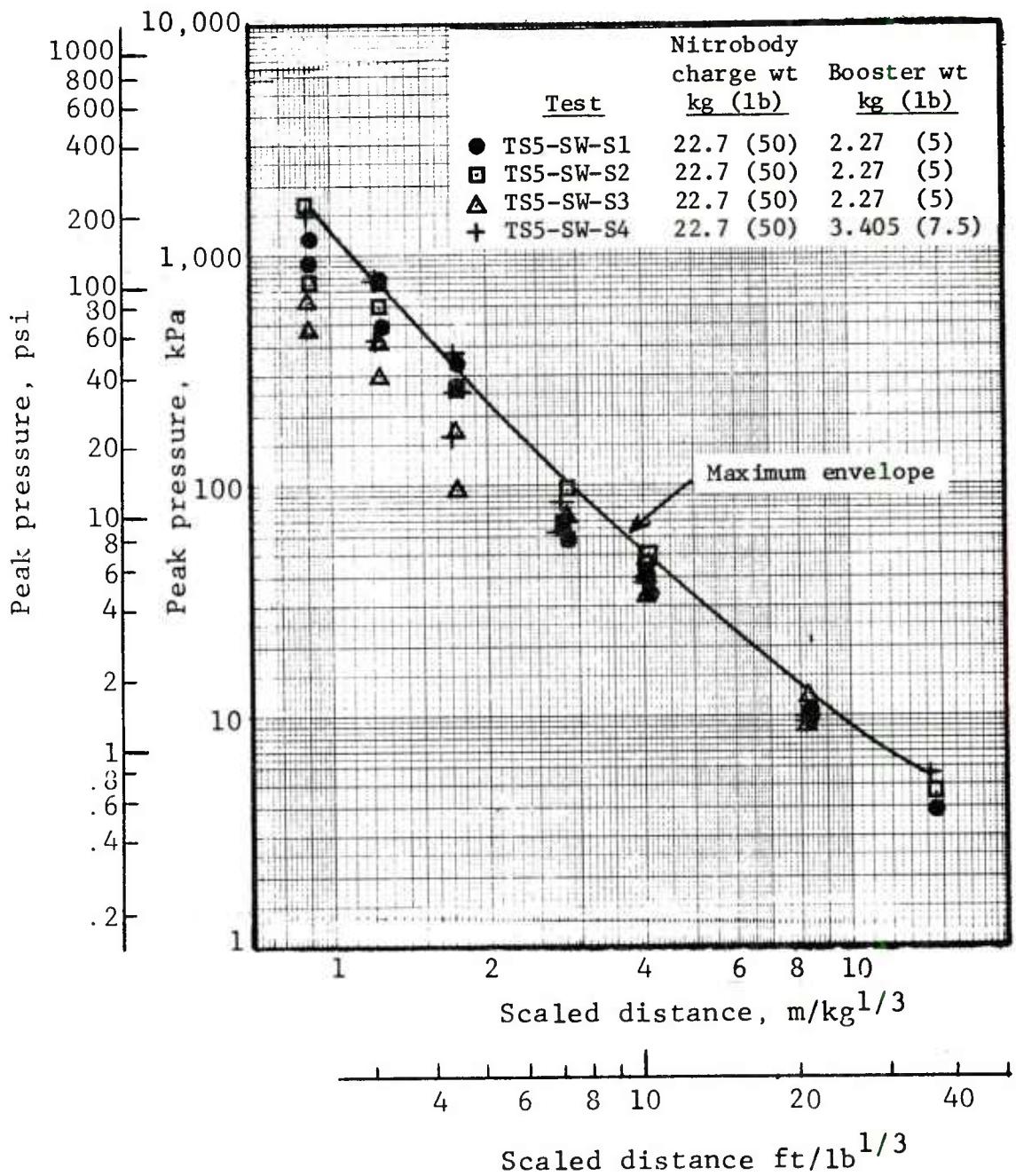
Table 22

Average reaction front velocities for acid wash tank
(dilute composition)

<u>Shot</u>	<u>Average reaction front velocity m/sec (fps)</u>	<u>Booster weight (% nitrobody present)</u>	<u>Special considerations</u>
1		10	
2	6808 (22,330)	10	• In all cases, some fragments were found, indicating low order or nondetonation
3		15	
4		15	• Based on the other acid wash tank data, the high reaction front velocity is questionable • The chemical mixture tested was incorrect-- much too dilute in nitrobody content.

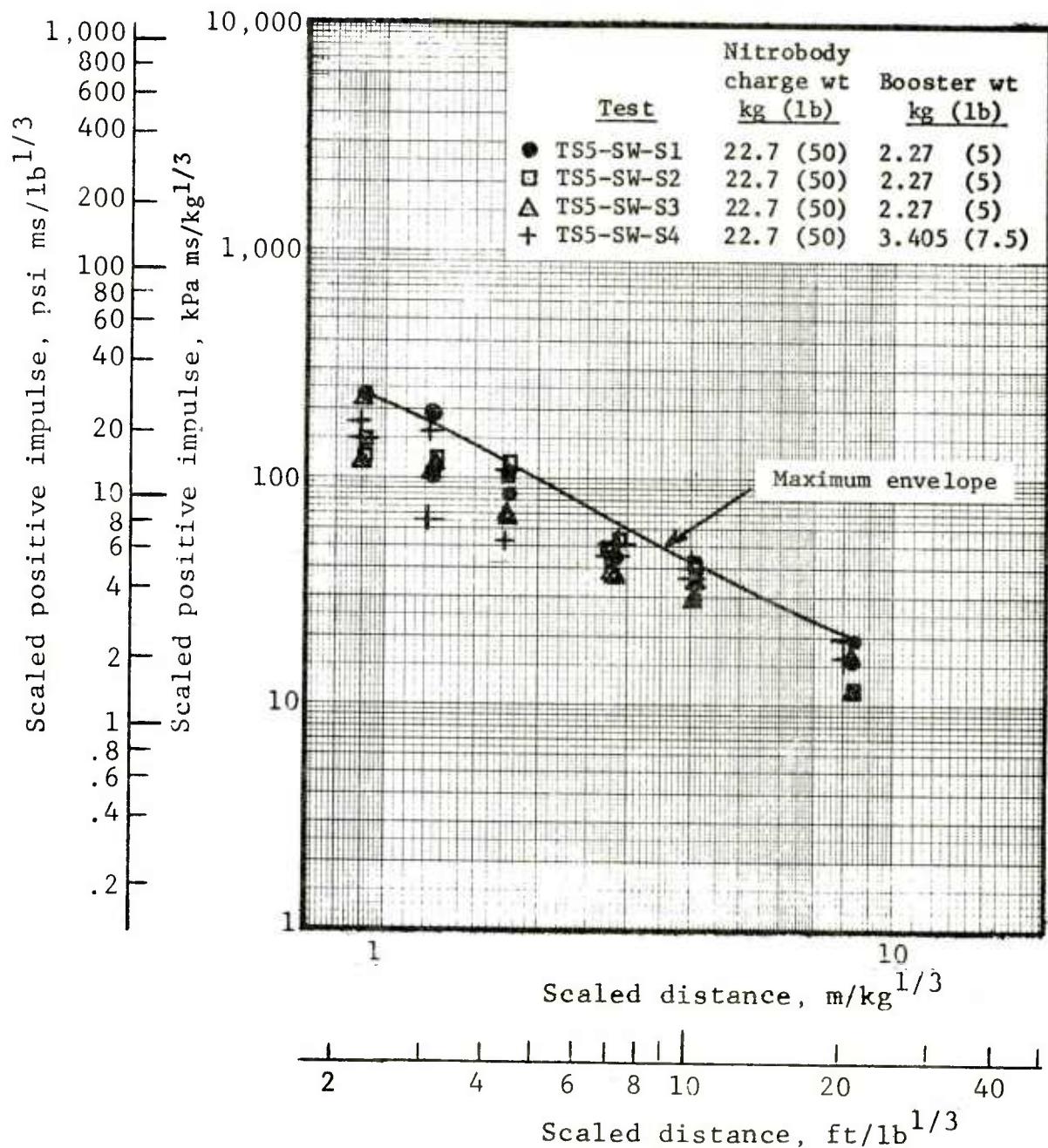
4.6 Test Results for Series 5 (old sellite wash tank)

The sellite wash tank is an agitated cylindrical tank with a draft tube and one spiral coil. The chemical mixture consists primarily of liquid TNT and water. In all sellite wash tank tests, the explosions were apparently low order (not a full detonation). A few pieces of cooling coil were found from shot 1, and shot 4 left black char on the blast pads. Detonation velocity was consistently only about 3000 m/sec (9800 fps). The four shots could be generally ordered with shots 2 and 1 having highest output and shots 3 and 4 having lowest output. Peak overpressure is plotted in figure 48; scaled positive impulse is given in figure 49; TNT equivalency percent is presented in figure 50; and reaction front velocity is summarized in table 23.



Test series 5

Fig 48 Peak pressure, sellite washer configuration, 22.7 kg (50 lb) nitrobody content



Test series 5

Fig 49 Scaled positive impulse, sellite washer configuration, 22.7 kg (50 lb) nitrobody content

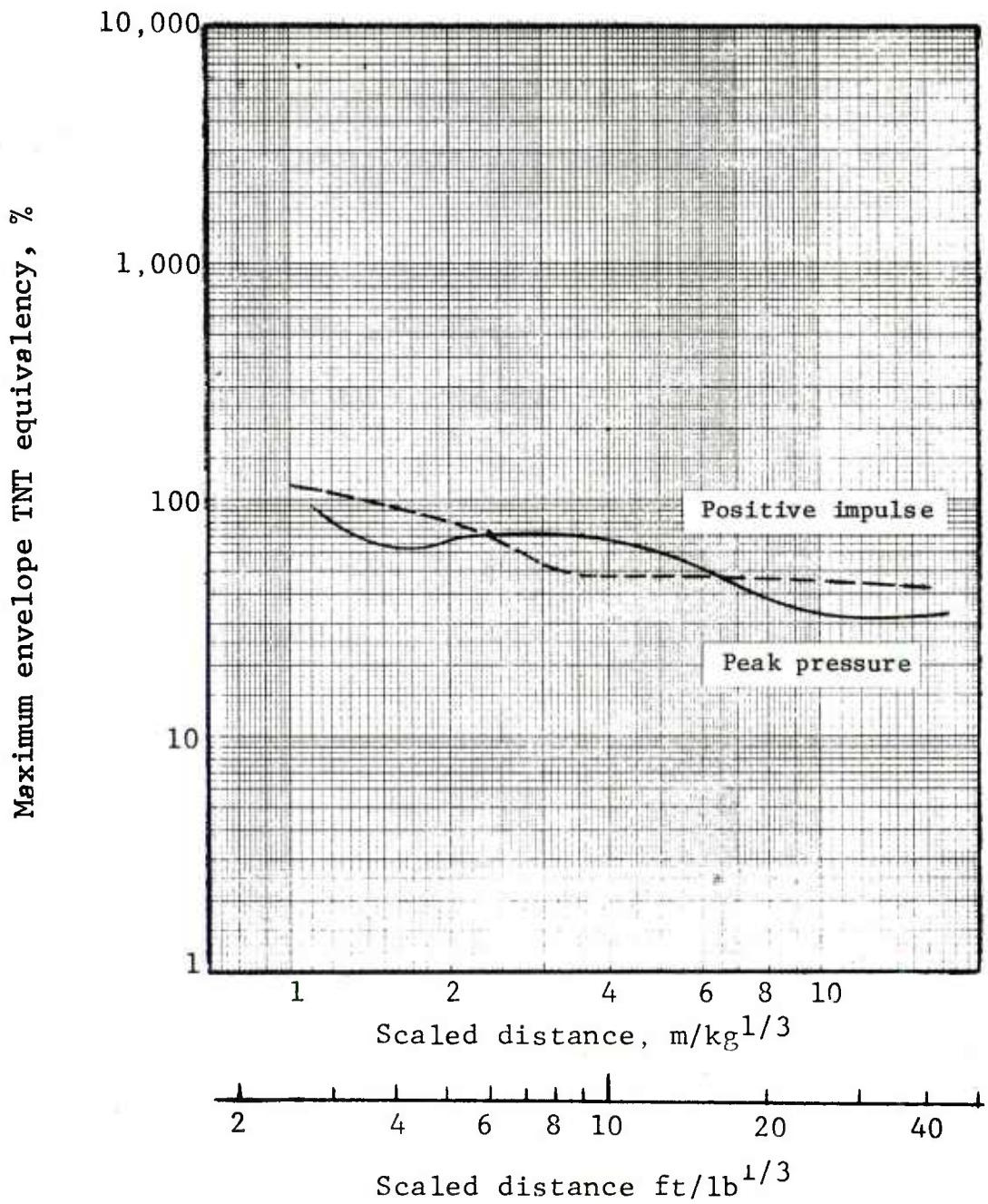


Fig 50 TNT equivalency, sellite washer configuration, 22.7 kg (50 lb) nitrobody content

Table 23

Average reaction front velocities for sellite wash tank

<u>Shot</u>	<u>Average reaction front velocity m/sec (fps)</u>	<u>Booster weight (% nitrobody present)</u>	<u>Special considerations</u>
1	2815 (9233)	10	Apparent detonation although some parts were found
2	3439 (11,280)	10	Apparent detonation
3	2989 (9804)	10	Apparent detonation
4	2855 (9364)	15	Apparent detonation

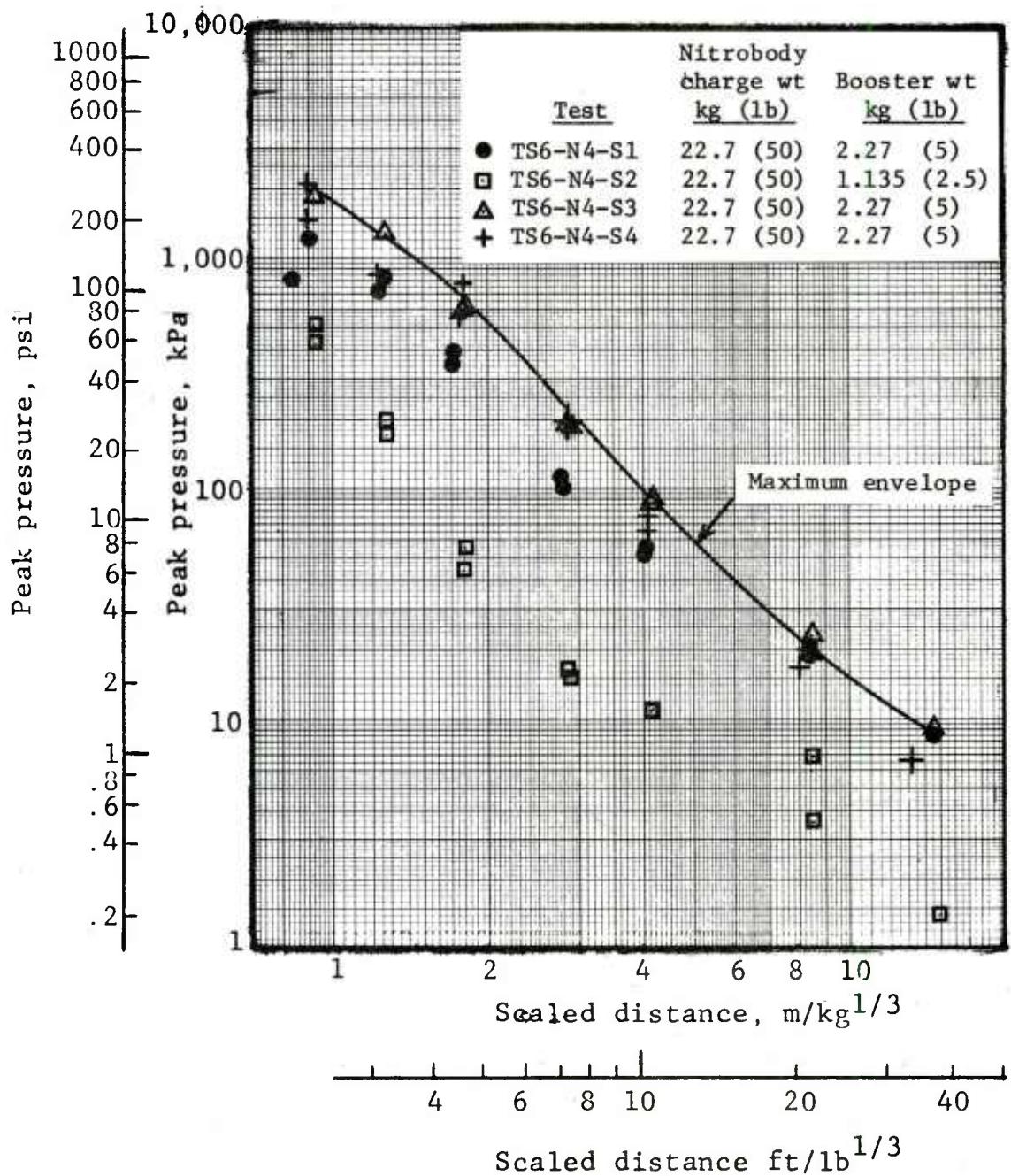
4.7 Test Results for Series 6 (new nitrator 4)

In the proposed system utilizing dynamic separators, new nitrator 4 will serve a parallel role to old nitrator 3A. However, new nitrator 4 is significantly more dilute in nitrobody content due to the quicker acting dynamic separators. Just as old nitrator 3A was simulated using a batch process, a batch process was required for nitrator 4.

Peak overpressure is presented in figure 51 and scaled positive impulse is given in figure 52. There is a very clear ordering in blast output within this series of shots. Perhaps, the more dilute nitrobody acid mixture accentuated the transition between low order reaction and full detonation. Shot 2 used a 5 percent booster and did not detonate. Shot 1 did detonate but clearly lies below shots 3 and 4 in figures 51 and 52. One possible explanation is a shorter TNT mixing duration in shot 1. In shot 1, TNT was agitated in the acid for only 30 min with a 10 min reaction time, whereas the TNT mixing time was 1 hr in both of shots 3 and 4.

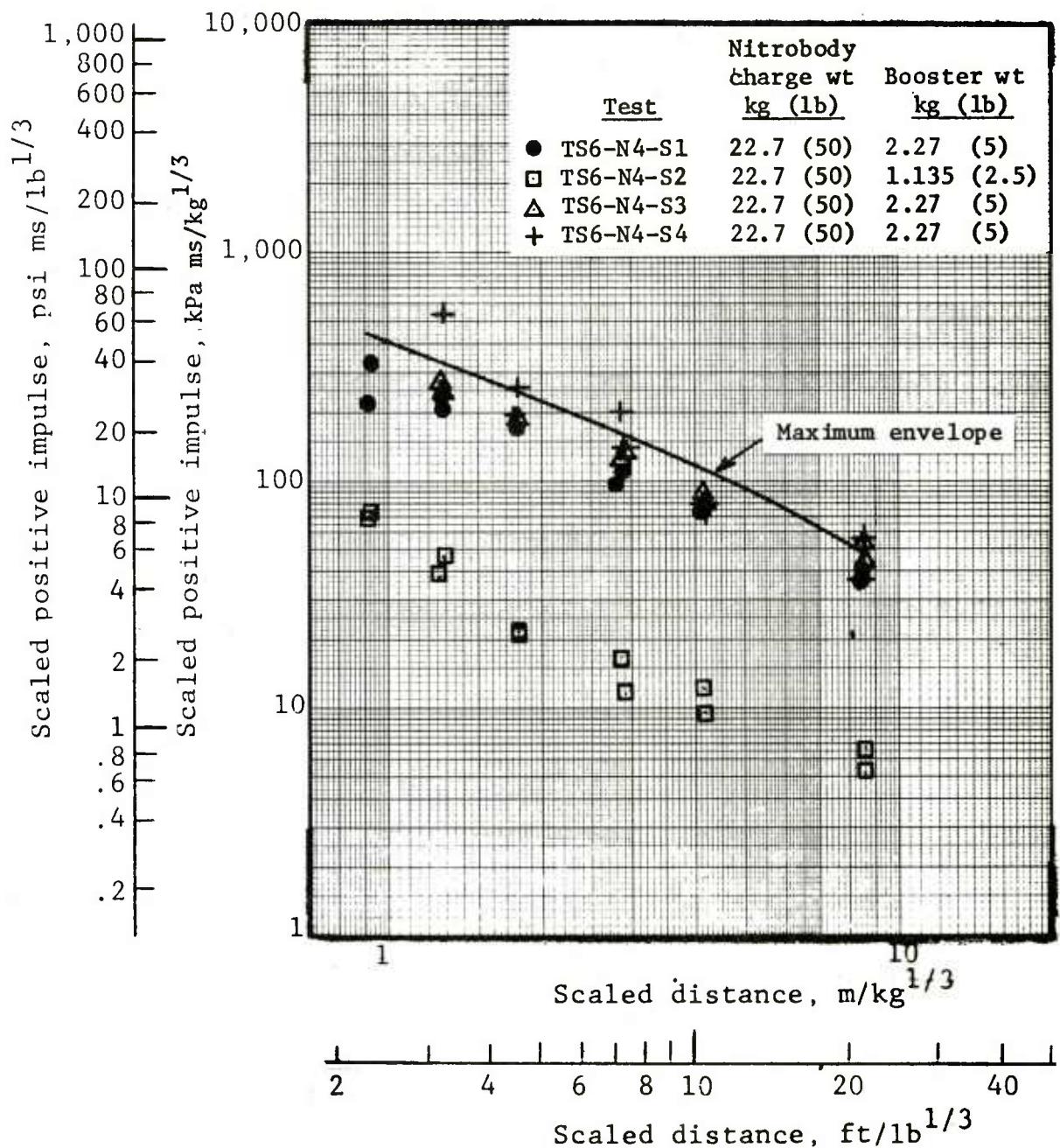
TNT equivalency is presented in figure 53 for the nitrator 4 series. Impulse equivalency is well above 200 percent for most of the scaled distances shown. Both pressure and impulse equivalencies drop with increasing scaled distances.

Detonation Velocity is summarized in table 24. The ordering of detonation velocities corresponds to the ordering of the shots based on blast output.



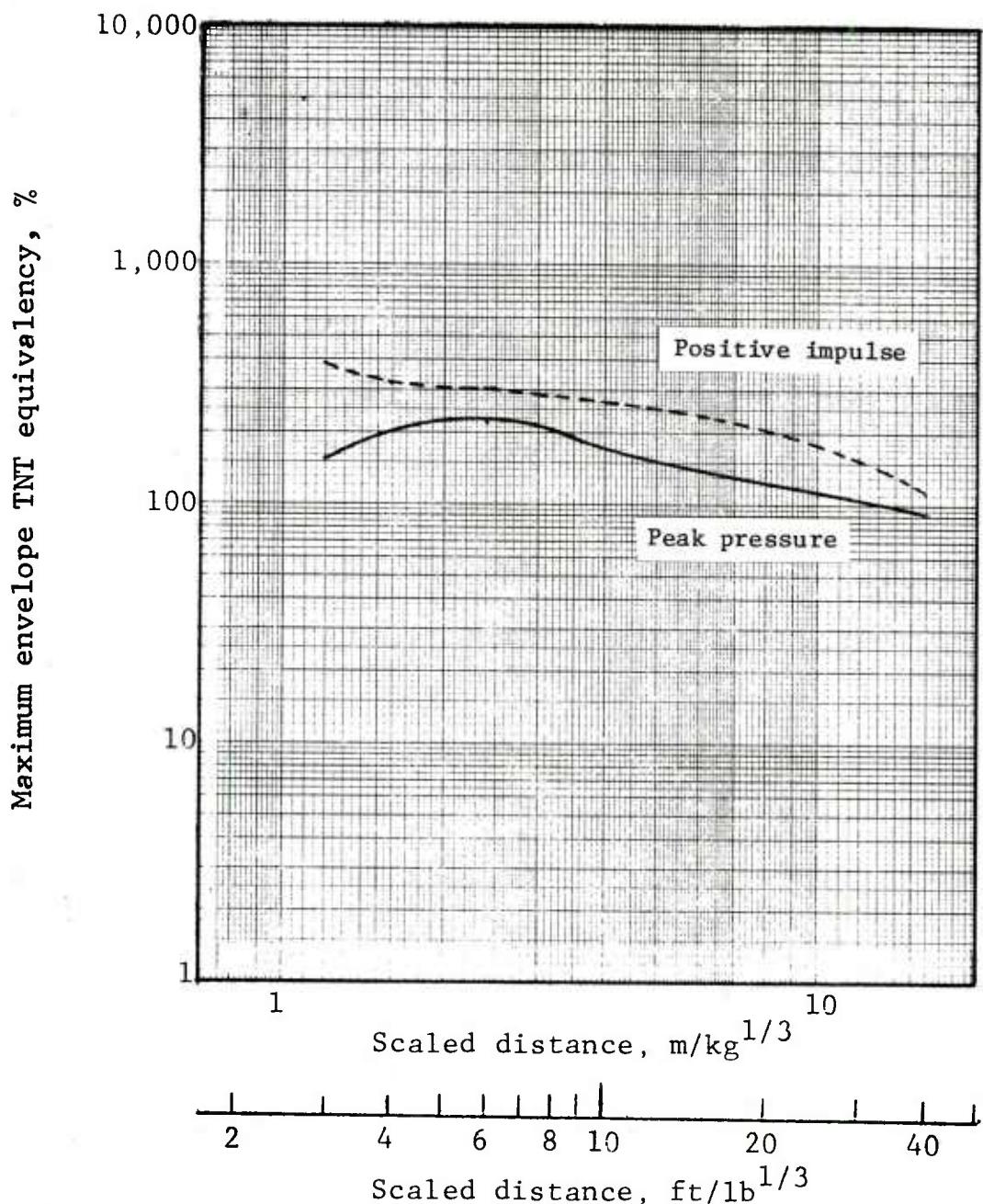
Test series 6

Fig 51 Peak pressure, new nitrator 4 configuration, 22.7 kg (50 lb) nitrobody content



Test series 6

Fig 52 Scaled positive impulse, new nitrator 4 configuration, 22.7 kg (50 lb) nitrobody content



Test series 6

Fig 53 TNT equivalency, new nitrator 4 configuration,
22.7 kg (50 lb) nitrobody content

Table 24

Average reaction front velocities for nitrator 4

<u>Shot</u>	<u>Average reaction front velocity m/sec (fps)</u>	<u>Booster weight (% nitrobody present)</u>	<u>Special considerations</u>
1	5558 (18,230)	10	Lowest output detonation of the series
2		5	Did not detonate
3	5793 (19,001)	10	High output detonation
4	7040 (23,091)	10	Highest output of the series

In the test plan for the new nitration reactors, a decision was to be made after testing nitrator 4. If nitrator 4 did not detonate in the first trial, new nitrator 5 (test series 7) would be tested. Nitrator 5 contains a higher TNT concentration and was considered to be more easily detonable than nitrator 4. If nitrator 4 detonated in the first trial, test series 7 would not be conducted. Since shot 1 of the nitrator 4 series clearly detonated, no nitrator 5 test was accomplished in this program.

4.8 Test Results for Series 8 (new nitrator 8)

New nitrator 8 in the proposed system utilizing dynamic separators serves an equivalent role to nitrator 6 in the old gravity separator system. Nitrator 8 is the last reactor in the chain. It contains primarily liquid TNT and nitrating acid and did not require a batch process for the simulation.

Three small-scale and one large-scale nitrator 8 tests were conducted, none of which exhibited a full detonation. In each case, the tank assembly was thrown off the blast pad a distance downrange. Large tank and draft tube fragments were discovered after the explosion. The coil system was found lying in the field like a large spring. The witness plate damage was due primarily to the booster, and the crater was quite small. Some unreacted acid was seen spilled near the blast center.

Peak overpressure versus scaled distance is plotted in figure 54 and scaled positive impulse is given in figure 55. TNT equivalency is presented in figure 56 showing the extremely low output from these tests. Impulse equivalency ranged between 12 and 60 percent. Thus the output was quite low, but not entirely due to the booster. Reaction front velocity data are summarized in table 25. The velocity data for the nitrator 8 series were fairly good, indicating that a reaction did propagate at between about 2000 and 3000 m/sec (about 7000 and 11,000 fps).

Table 25

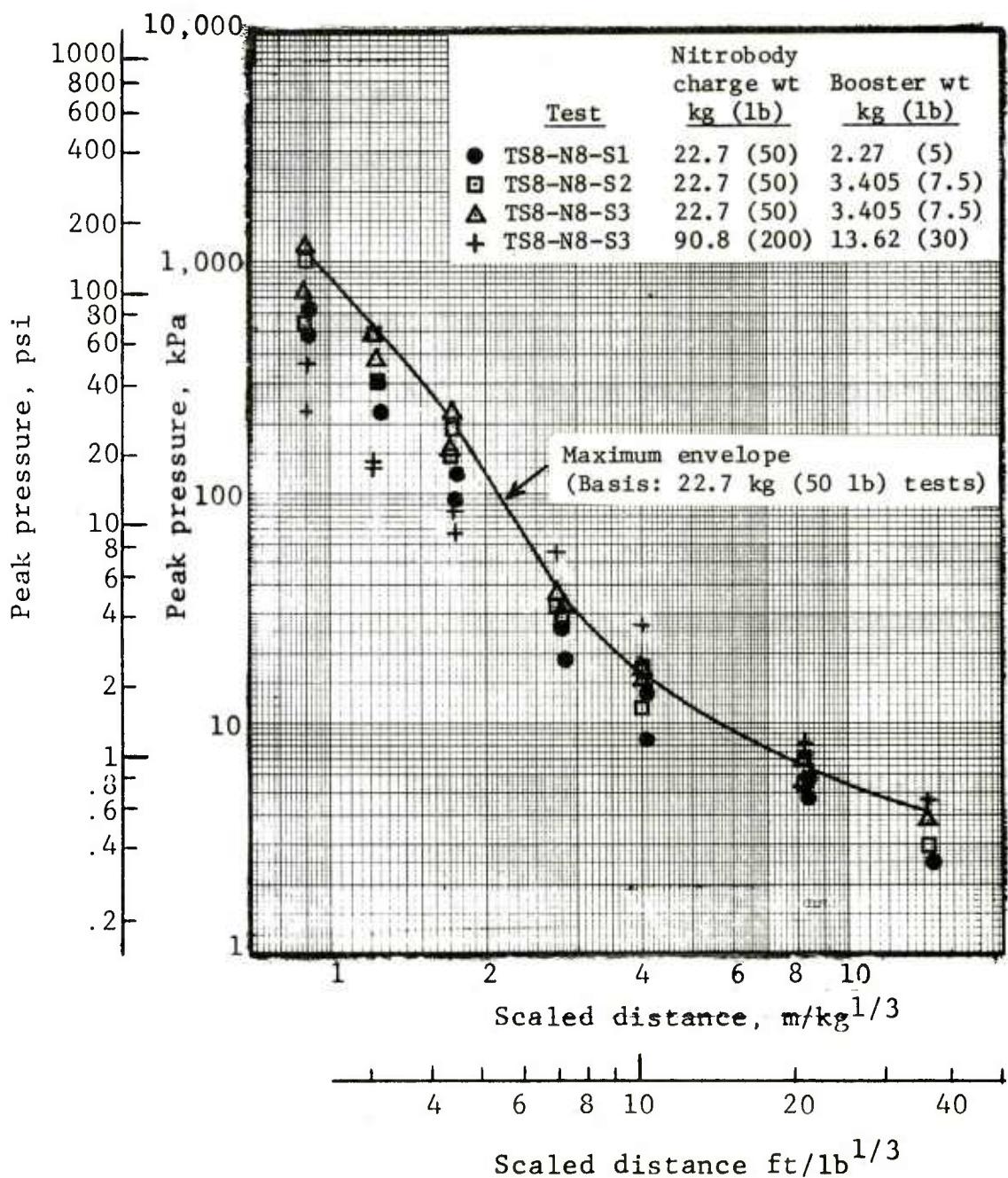
Average reaction front velocities for nitrator 8

<u>Shot</u>	<u>Average reaction front velocity m/sec (fps)</u>	<u>Booster weight (% nitrobody present)</u>	<u>Special considerations</u>
1	3209 * (10,526)	10	Did not detonate
2	2675 (8774)	15	Did not detonate
3	2135 (7003)	15	Did not detonate

* Average included data from probe located in booster.

4.9 Calibration Shots

During this program, nine calibration shots were conducted. In most cases, these consisted of detonating a 2.27 kg (5 lb) C-4 explosive hemisphere on a steel witness plate at ground level (tests CAL-1 through CAL-6). Peak overpressure and scaled positive impulse from each shot were plotted on standard curves for anticipated C-4 hemisphere output. Whenever a pressure transducer produced a questionable signal (not attributable to acceptable experimental data scatter), the gage was replaced and the circuit inspected for problems prior to the next test. The 2.27 kg (5 lb) calibration shots are plotted in figures 57 through 62.



Test series 8

Fig 54 Peak pressure, new nitrator 8 configuration, 22.7 kg (50 lb) and 90.8 kg (200 lb) nitrobody content

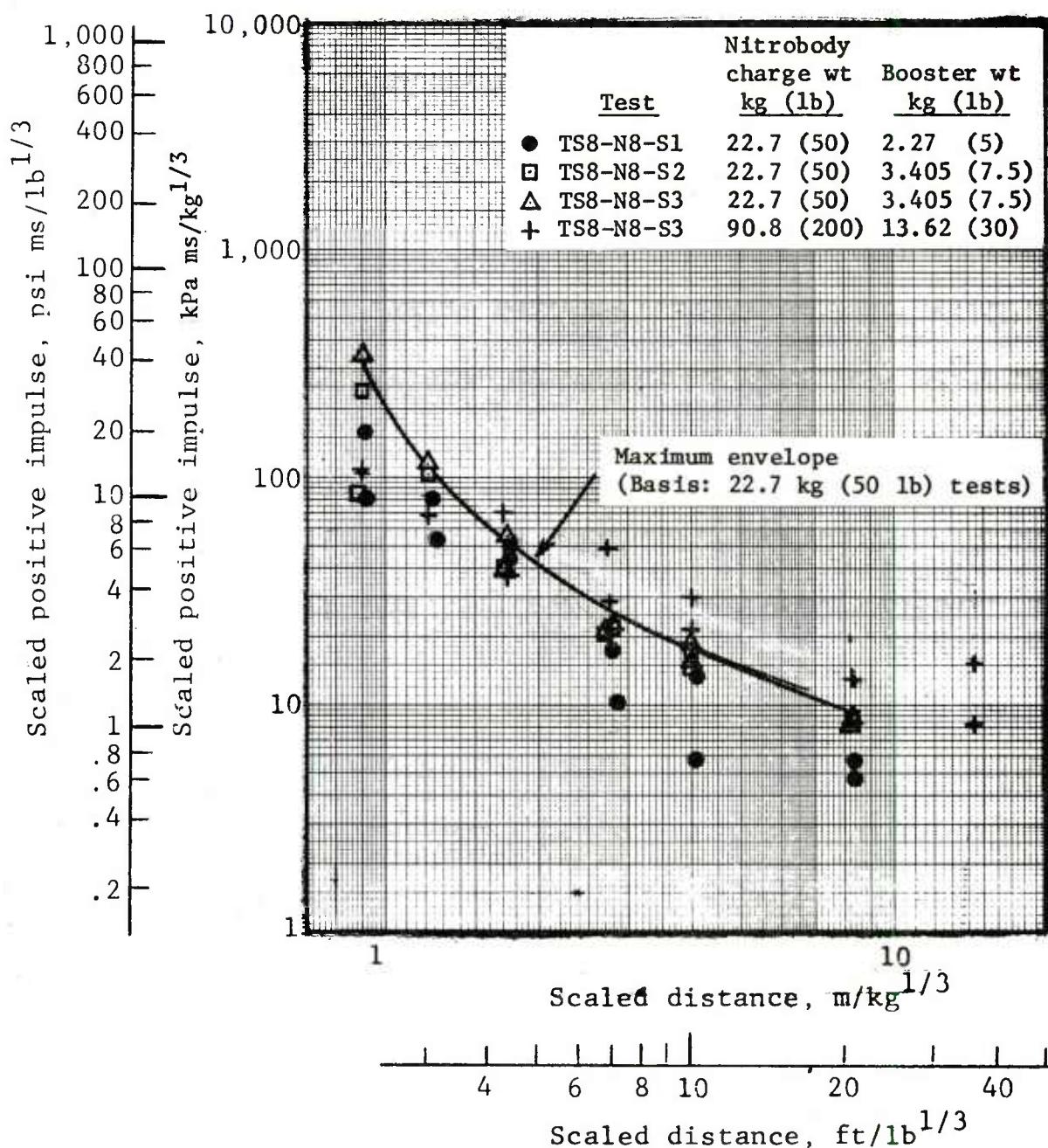
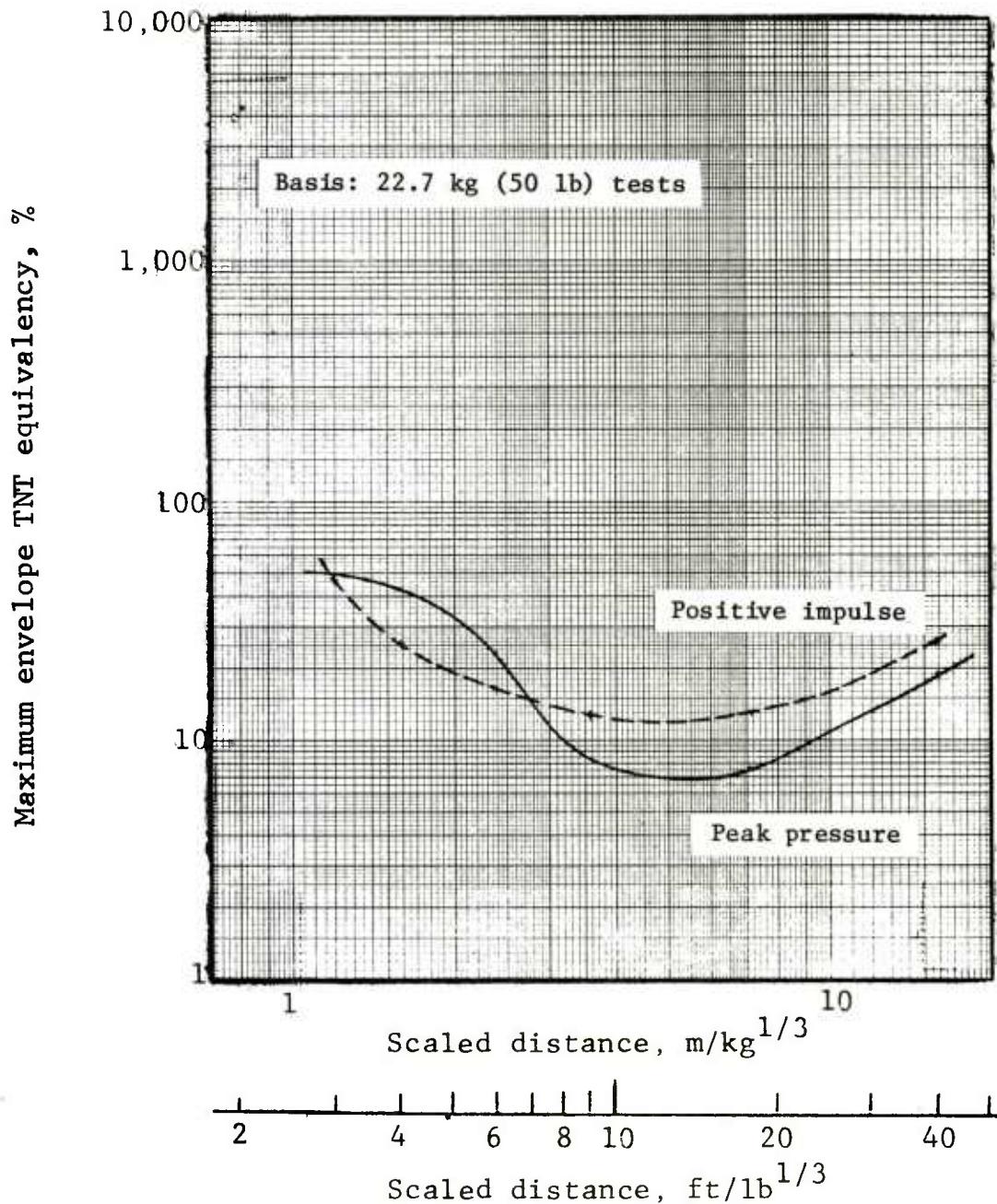


Fig. 55 Scaled positive impulse, new nitrator 8 configuration, 22.7 kg (50 lb) and 90.8 kg (200 lb) nitrobody content



Test series 8

Fig 56 TNT equivalency, new nitrator 8 configuration, 22.7 kg (50 lb) nitrobody content

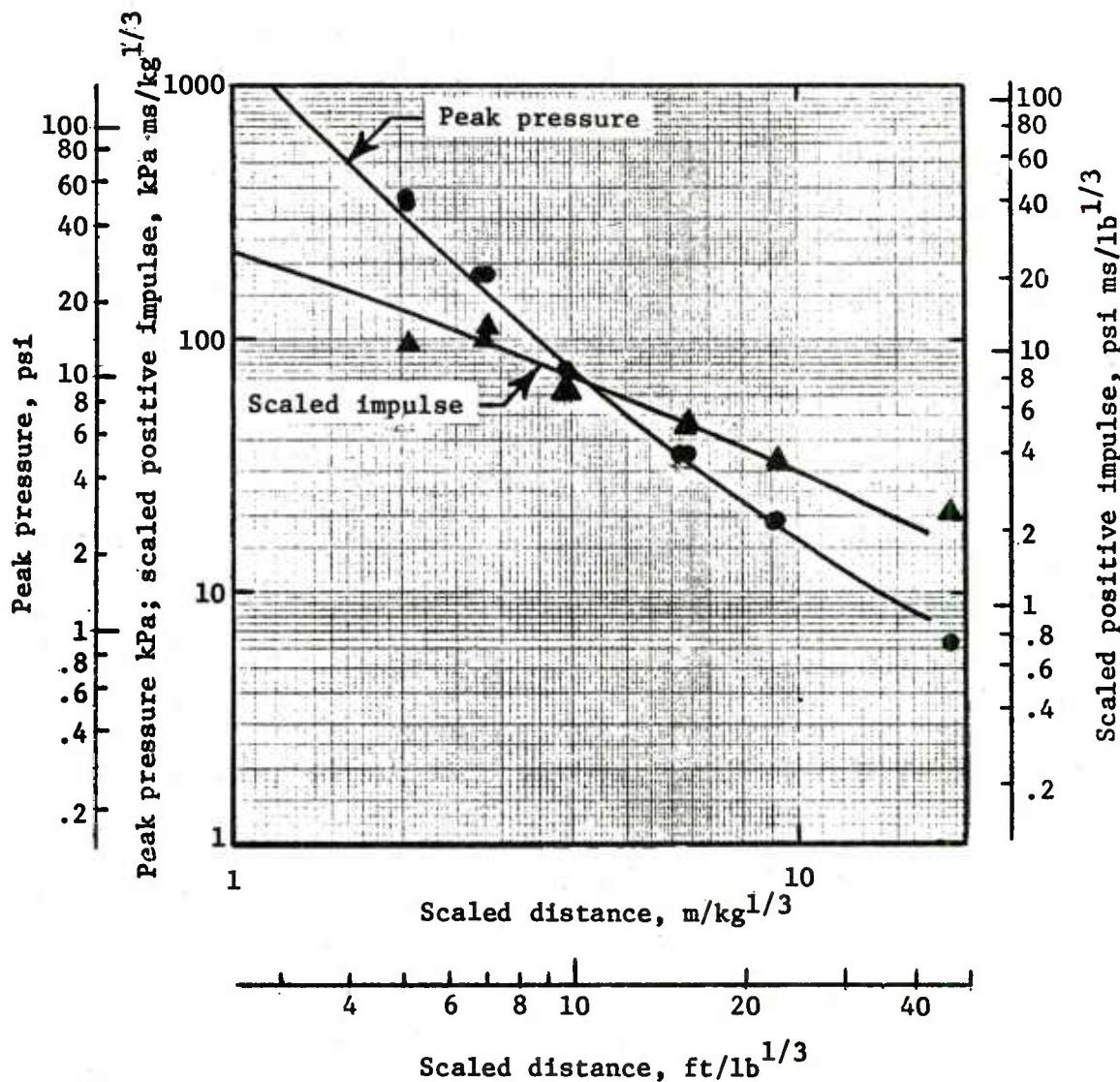


Fig 57 CAL-1 C-4 verification test,
2227 kg (5 lb) hemisphere

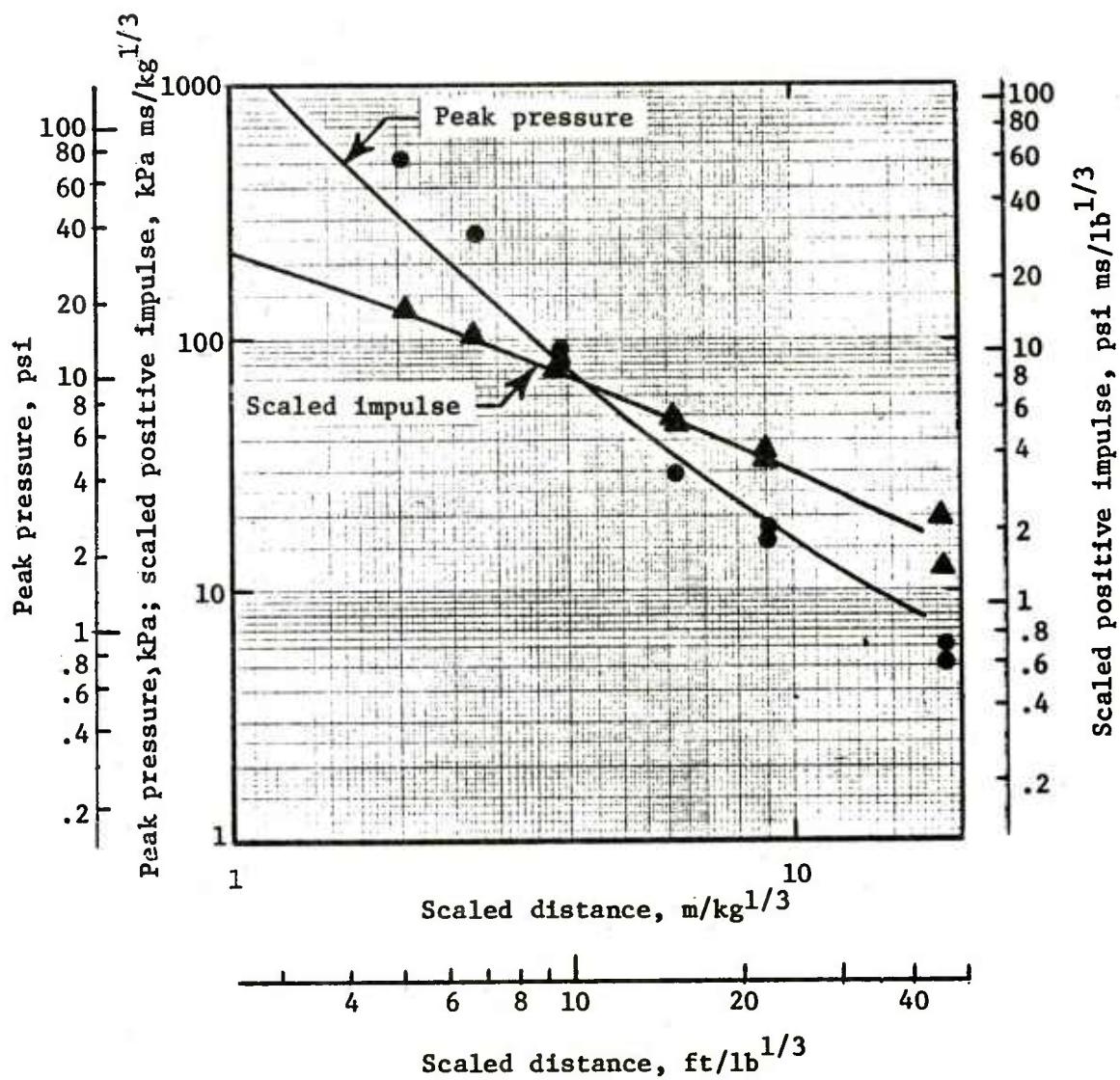


Fig 58 CAL-2 C-4 verification test,
2.27 kg (5 lb) cylinder L/D=2

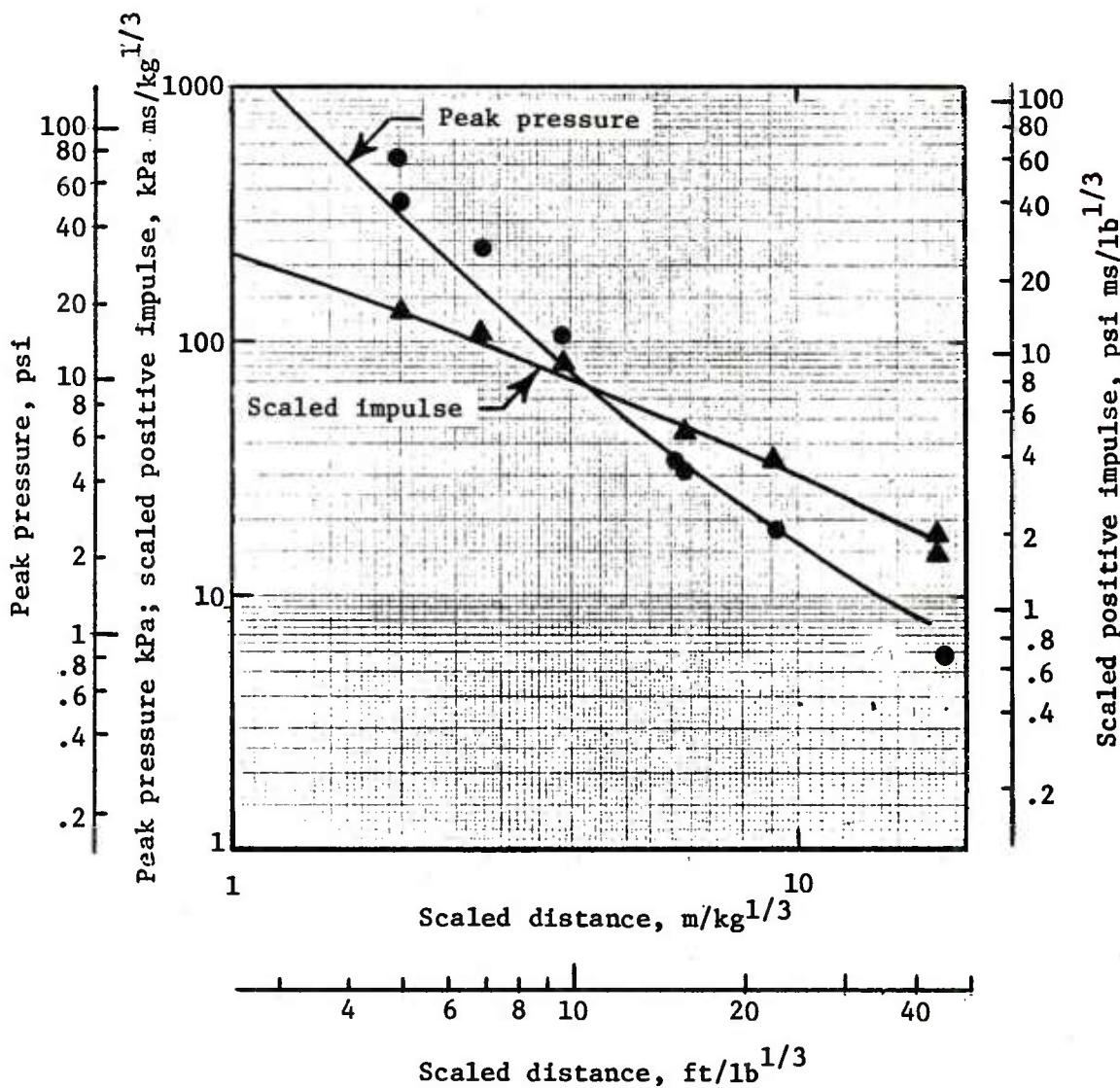


Fig 59 CAL-3 C-4 verification test,
2.27 kg (5 lb) hemisphere

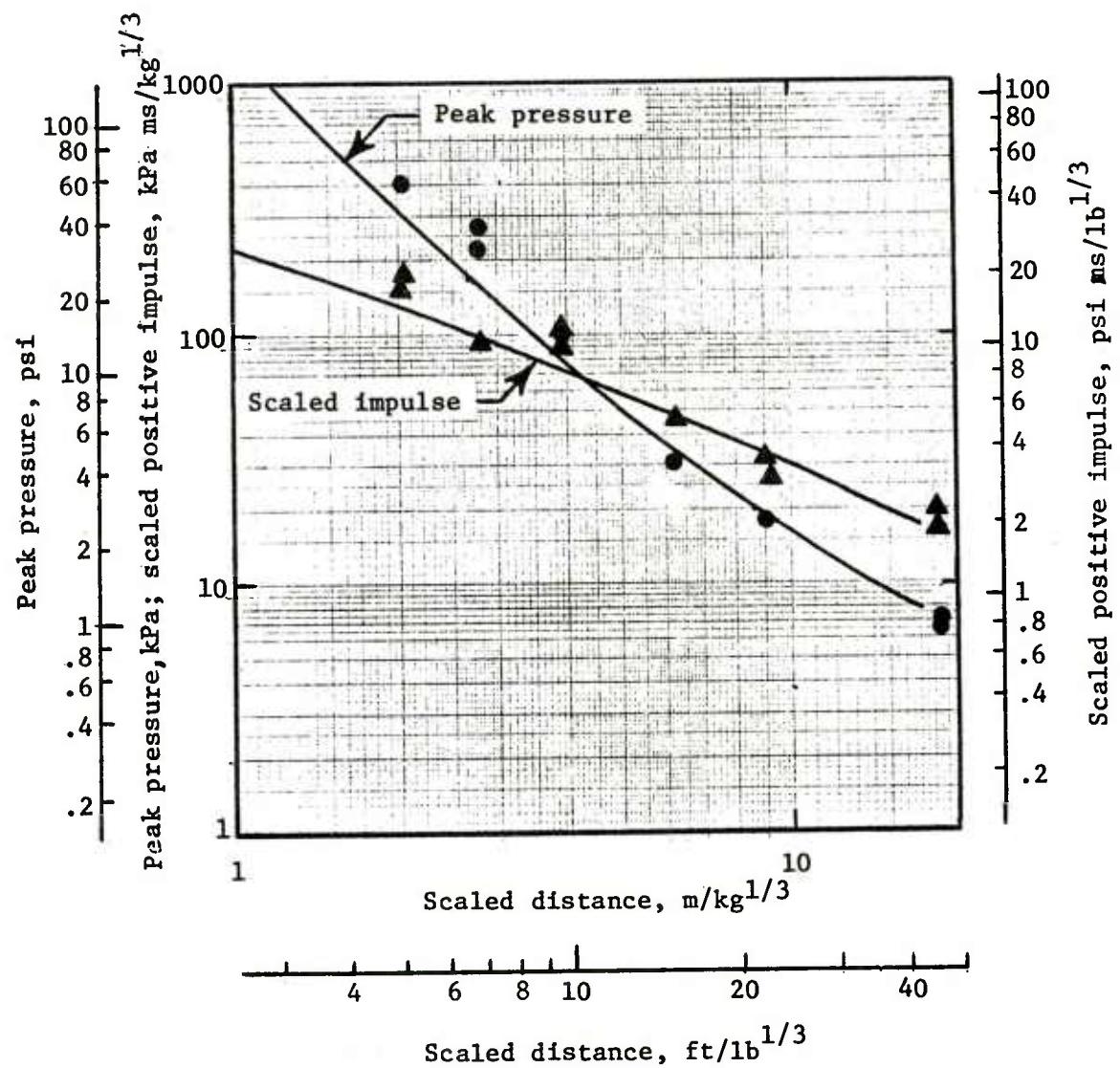


Fig 60 CAL-4 C-4 verification test,
2.27 kg (5 lb) hemisphere

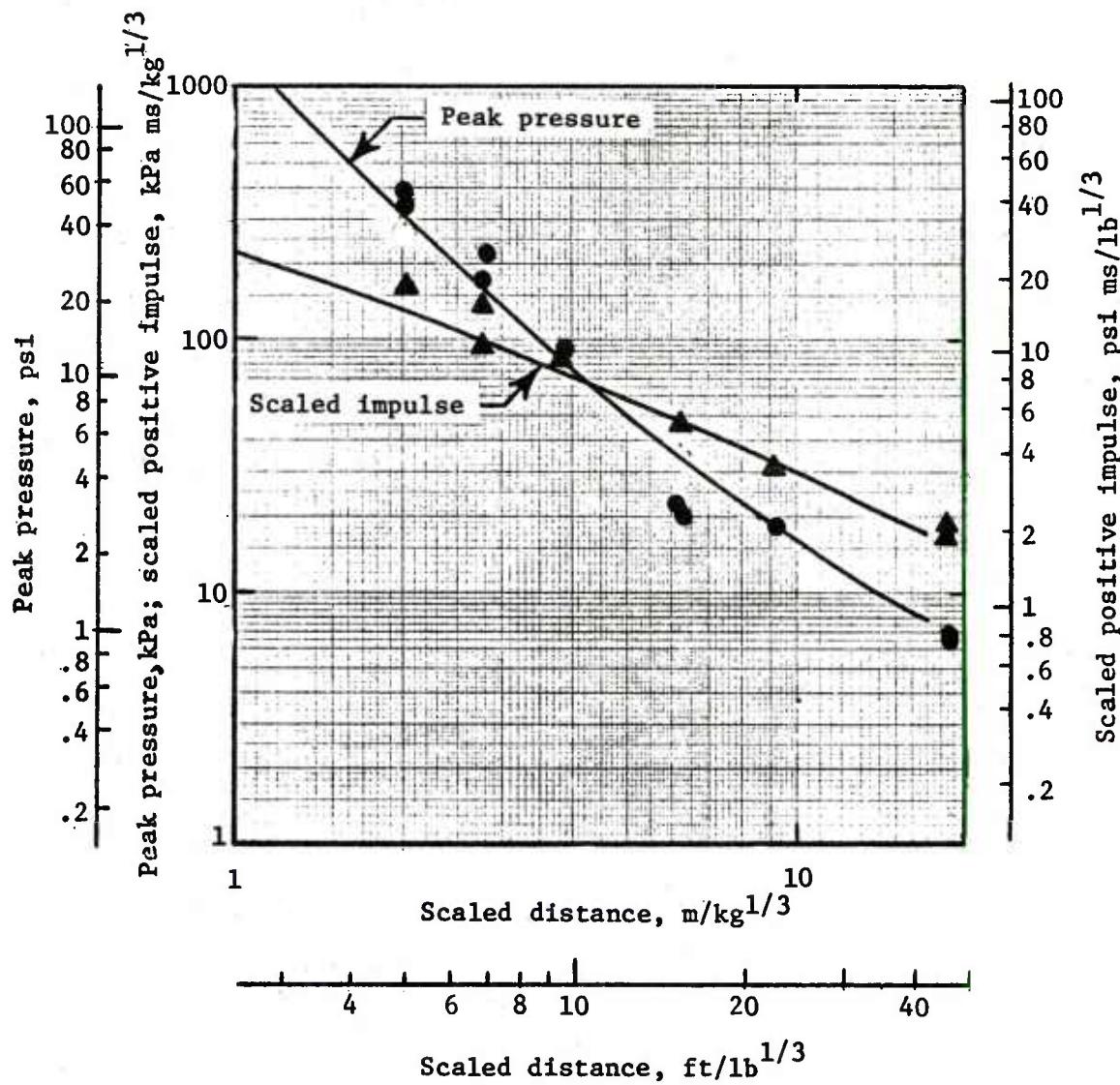


Fig 61 CAL-5 C-4 verification test,
2.27 kg (5 lb) hemisphere

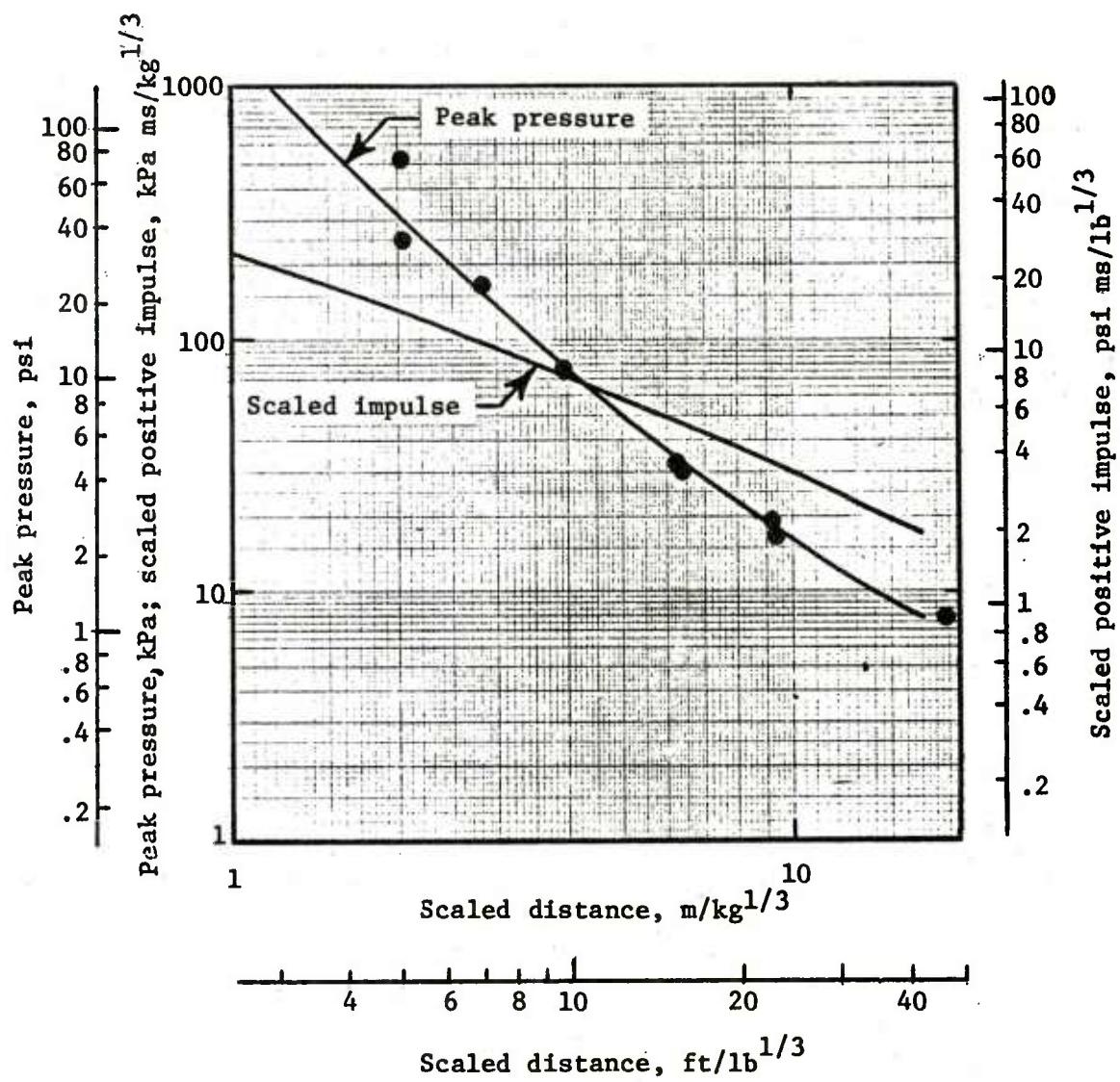


Fig 62 CAL-6 C-4 verification test,
2.27 kg (5 lb) hemisphere

In anticipation of the large-scale testing conducted at the National Space Technology Laboratories, one 18.75 kg (41.3 lb) explosive C-4 hemisphere (CAL-7) was detonated at the IITRI Indiana test site. The data from this shot are given in figure 63.

A 19 kg (42 lb) TNT cylinder with a 1.73 length to diameter ratio (CAL-8) was detonated to give a good qualitative comparison for the nitration reactor shots. The blast output, witness plate damage, and crater size from this shot were considerably less than that produced by most of the nitrator 3A, nitrator 6, separator 6, and nitrator 4 tests. The peak overpressure and scaled positive impulse data for this shot are plotted in figure 64.

At the National Space Technology Laboratories, a 18.75 kg (41.3 lb) C-4 explosive hemisphere was detonated prior to accomplishing the large-scale nitrator 8 shot. The results of this calibration shot are presented in figure 65.

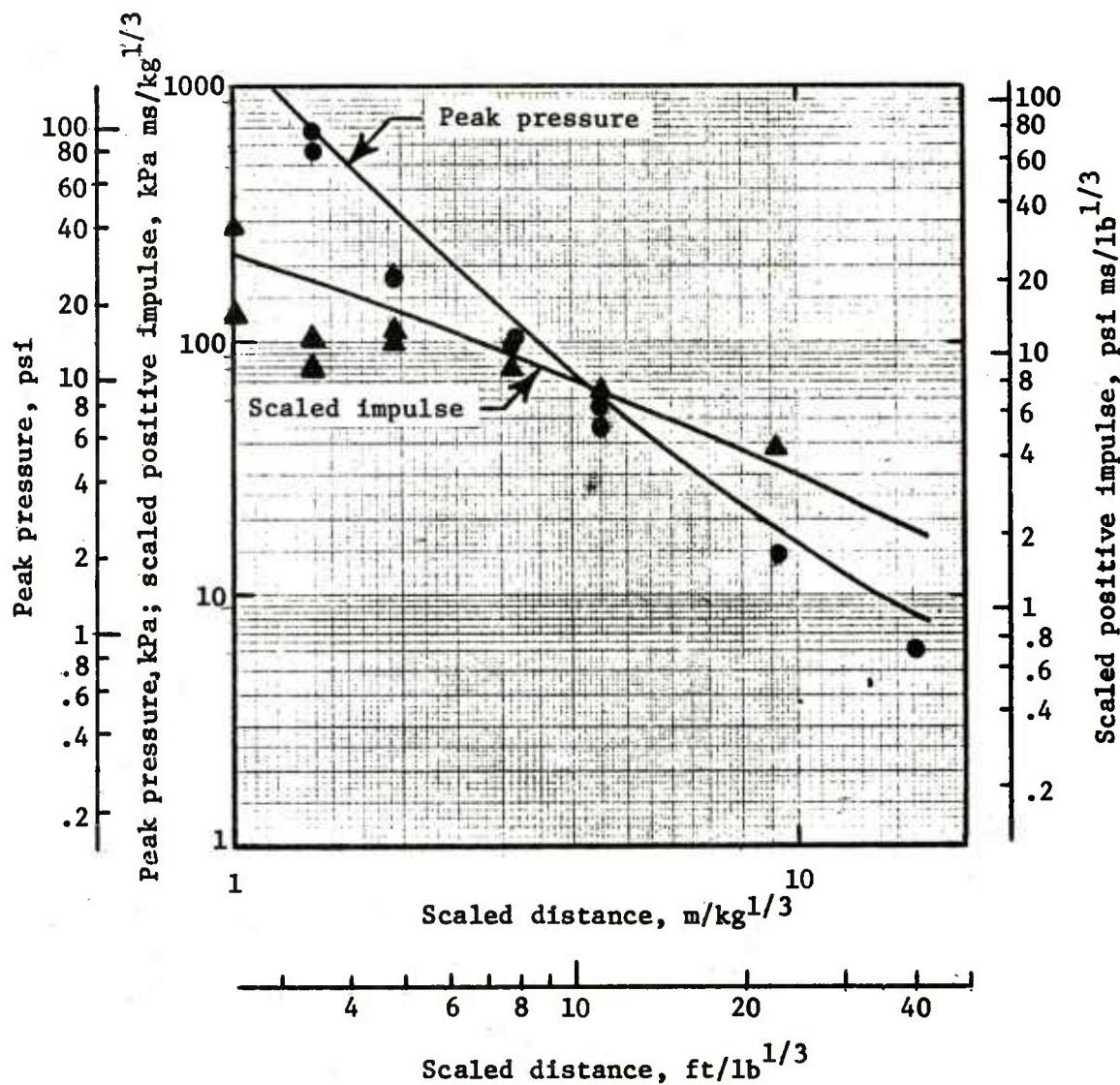


Fig 63 CAL-7 C-4 verification test,
18.75 kg (41.3 lb) hemisphere

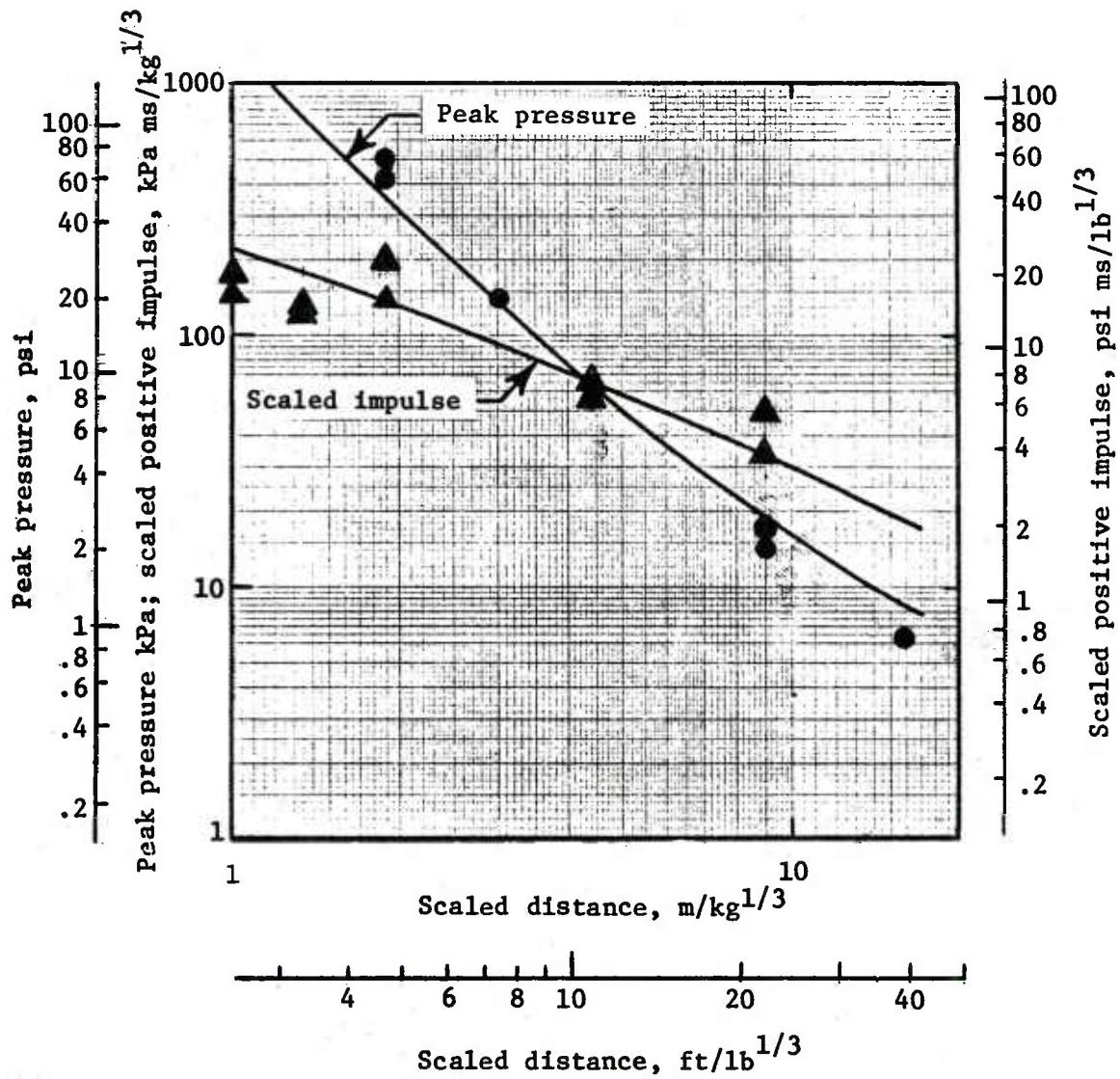


Fig 64 CAL-8 Solid TNT cylinder calibration test,
L/D=1.75, 19.068 kg (42 lb)

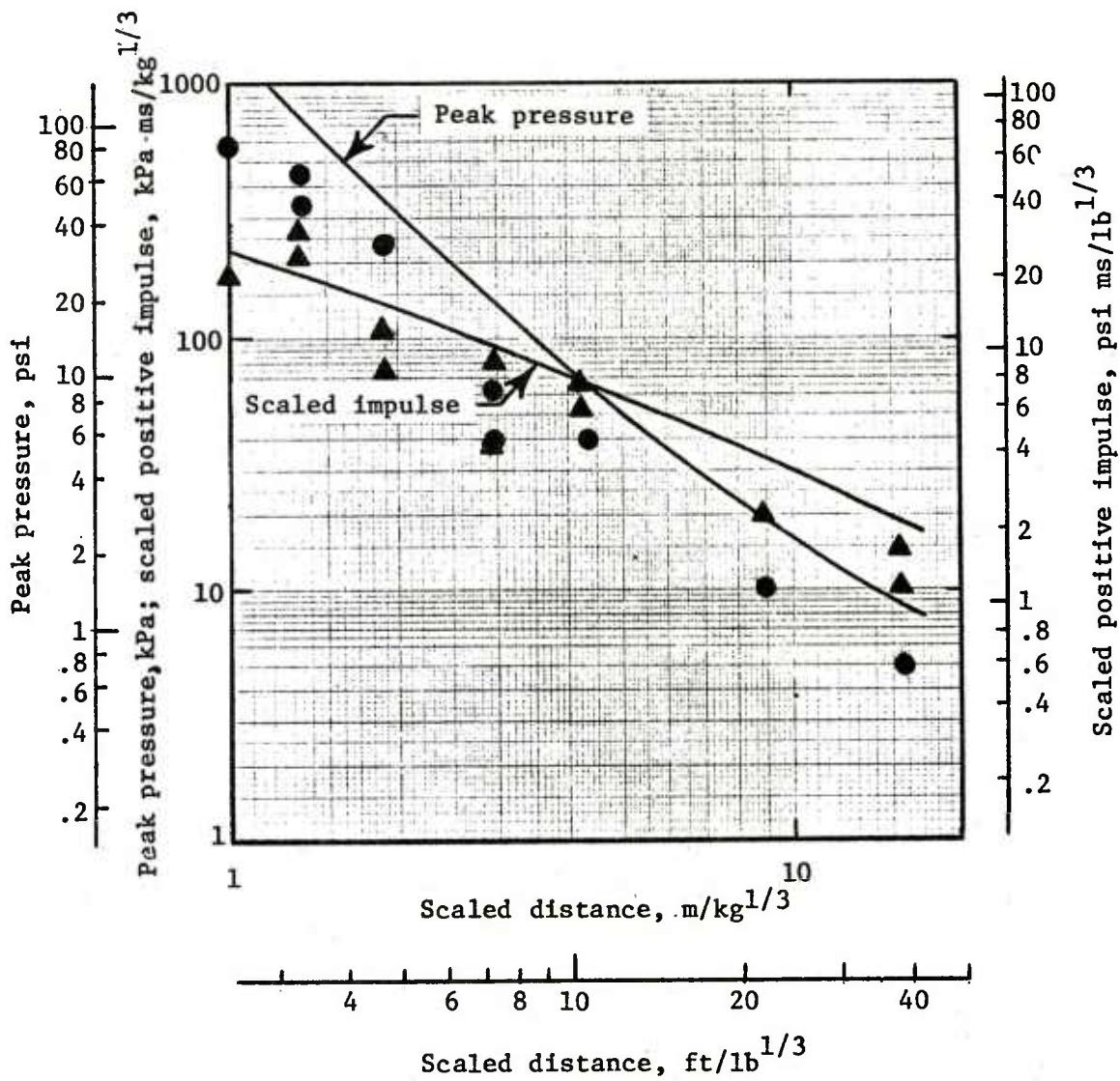


Fig 65 CAL-9 (NSTL) C-4 verification test,
18.75 kg (41.3 lb) hemisphere

5. ANALYSIS OF DATA AND CONCLUSIONS

In this section analyses and discussions are presented to clarify what has been learned during the program. First, a technique for prediction of explosive airblast output requiring a minimum of tests is described. This technique correlates the data obtained in the program quite well and is used to predict peak overpressure, positive scaled impulse, and TNT equivalencies for the acid wash tank (for which experimental data are lacking). Second, the TNT process vessels tested in this program required intense stimuli to initiate detonation. They were quite insensitive. The information on sensitivity which can be deduced from the test results is presented and discussed. Finally, major conclusions which have resulted from this program are summarized.

5.1 Prediction of Explosive Airblast Output

In this section, a methodology is described for prediction of explosive airblast output produced by the detonation of complex chemical process components, such as exist in a continuous TNT process plant.

5.1.1 Description of Methodology

The first step is to analytically predict the energy released in the detonation of the process chemical under consideration. An energy equivalency can then be defined as the ratio of the process chemical energy release to the energy release of an equal quantity of TNT (X 100%).

Once the energy equivalency of each process chemical mixture is computed, experimental data can be correlated quite well by modifying the scaled distance λ and scaled positive impulse $I/W^{1/3}$ using the energy equivalencies. The scaling factor is derived by making the assumption that for similar geometric configurations, the same peak overpressure and scaled positive impulse will be generated at the same scaled distances regardless of composition if the following TNT equivalent weight is used to correlate the data.

$$W_{TNT} = \underbrace{\left(\begin{array}{l} \text{Weight of} \\ \text{Chemical 1} \end{array} \right)}_{W_1} \left(\begin{array}{l} \text{Energy} \\ \text{Equivalency} \\ \text{of Chemical 1} \end{array} \right) = \underbrace{\left(\begin{array}{l} \text{Weight of} \\ \text{Chemical 2} \end{array} \right)}_{W_2} \left(\begin{array}{l} \text{Energy} \\ \text{Equivalency} \\ \text{of Chemical 2} \end{array} \right) \quad \varepsilon_1 \quad \varepsilon_2$$

Thus, the scaling factor (multiplier for both λ and $I/W^{1/3}$) used to condense the experimental data onto a 100 percent TNT equivalent curve is given by

$$f = \left(\frac{100}{\epsilon} \right)^{1/3}$$

where ϵ is the energy equivalency of the process chemical mixture being considered. It is shown below that the data for the wide variety of chemical compositions tested in cylindrical outer containers in this program does indeed condense quite well onto a single curve for peak overpressure and reasonably well for scaled positive impulse.

Since it is shown that the data correlates well using this technique, it is reasonable to assume that one can work backward and predict airblast output for process vessels of similar geometry and similar composition which have not been tested. In other words, it appears possible to conduct a single series of tests (e.g., for nitrator 4) and use those test results to predict reasonably well the airblast output for all the other similar vessels in the process (e.g., nitrators 3A, 6, 5, and 8, the sellite wash tank, and the acid wash tank). Since the acid wash tank data produced in this program were for a dilute mixture, the methodology described above is used to predict the actual acid wash tank compartment airblast output.

5.1.2 Prediction of Energy Equivalencies for the Chemical Mixtures Tested

In each nitrobody system tested, an oil phase existed as droplets of TNT and/or DNT suspended in an acid mixture. The acid contained dissolved nitrobody. Whether as droplets or in solution, the nitrobody was in good physical contact with the acid at the time of detonation. In this situation, unless chemicals extraneous to the explosive component survive the detonation unchanged, both chemically and physically, they will in fact affect the overall energy output of the detonating system. The effects of these "additives" can be endothermic or exothermic; water, which will change phase from liquid to gas will abstract energy to compensate for its heat of vaporization (along with rise in temperature). Nitric acid, which will yield oxygen to oxidize excess fuel, convert CO to CO₂, etc., will add energy in accordance with appropriate heats of reactions involved, less energy consumed for vaporization/temperature increases. Thus, the overall stoichiometry of the total chemical system has to be considered.

5.1.2.1 Energetic Considerations

In these systems the nitrobody explosives and acids, including excess water, were mixed. Whether dissolved or dispersed, heterogeneous or homogeneous, it must be anticipated that if the system detonated, all components thereof would participate in the reaction. Therefore the calculations that follow were made on the basis that all components participated in the chemical reaction and the energy exchanges are associated therewith. Water and the water component in the acids reverted to water only, except that the product water was also assumed to be a gas.

The calculations were performed by initially breaking down all components to their elemental state, based on the following heats of formation:

• H ₂ O (l)	68.39	kcal/mole
• H ₂ O (g)	57.83	kcal/mole
• CO (g)	26.43	kcal/mole
• CO ₂ (g)	94.38	kcal/mole
• SO ₂ (g)	69.30	kcal/mole
• SO ₃ (g)	91.52	kcal/mole
• HNO ₃ (l)	42.37	kcal/mole
• H ₂ SO ₄ (l)	189.75	kcal/mole
• DNT (l)	28.1	kcal/mole
• TNT (l)	29.1	kcal/mole

The products were then assumed to be:

- all hydrogen was oxidized to H₂O (g)
- as far as carbon is concerned, two alternative calculations were conducted:
 - (1) All carbon oxidized was oxidized to CO₂ with excess carbon remaining as carbon.
 - (2) All carbon present was oxidized to CO and any remaining O₂ was consumed in oxidizing CO to CO₂.
- all nitrogen went to N₂ (g); i.e., no nitrogen oxides were considered.
- all sulphur remained as sulphur, except where excess O₂ remained after all carbon was oxidized to CO₂; then

- (1) Excess oxygen oxidized all possible sulphur to SO_2 .
- (2) If all sulphur present could be oxidized to SO_2 and oxygen still remained, then it oxidized SO_2 to SO_3 .

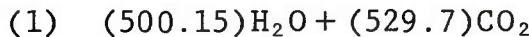
The basis for all calculations were 22.7 kg (50 lb) of nitrobody. In the case of TNT(s), 22.7 kg (50 lb) of TNT are equivalent to 100 gm-mole TNT. The value of 29.1 kcal/mole was used in these calculations; other values are reported and could just as well have been used. The overall result would be different values for the heats of reaction that were obtained, but the relative ranking would be much the same. The same applies to the value for DNT.

If 22.7 kg (50 lb) of TNT is reduced to its elements, a total of 2910 kcal would be required. If the detonation products are H_2O , CO_2 , C and N_2 , then the heat of reaction would be 1.24 kcal/gm of TNT. If the products are H_2O , CO, C and N_2 , then the heat of reaction would be 0.92 kcal/gm TNT. According to data in Urbansky (reference 5), these values are given:

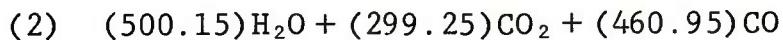
- TNT at 1.59 cm/cc: 1.085 kcal/gm
- TNT at 1.00 gm/cc: 0.910 kcal/gm
- Kast calculations: 0.950 kcal/gm

If the average of the two values calculated is taken, which implies an equilibrium of about 50: 50 for CO and CO_2 (which approximation is close to the assumed decomposition products by Kast) then the resulting value is 1.08 kcal/gm. For equivalency calculations, it is assumed that high density TNT is being considered as the standard; therefore, even though equivalency calculations may be based on no CO and all CO_2 , which is in accord with the work of Kamlet, the comparison should be made to TNT equivalency based on the best available information. Therefore it is assumed that the heat of reaction of TNT in detonation is 1.08 kcal/gm.

Test series 1 (old nitrator 3A

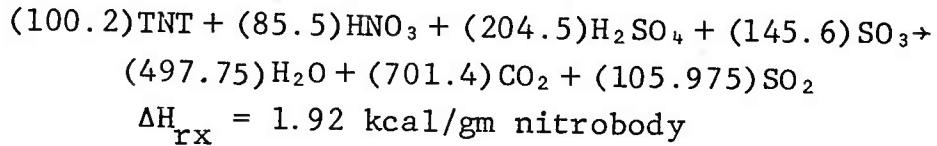


$$\Delta H_{rx} = 1.58 \text{ kcal/gm nitrobody}$$

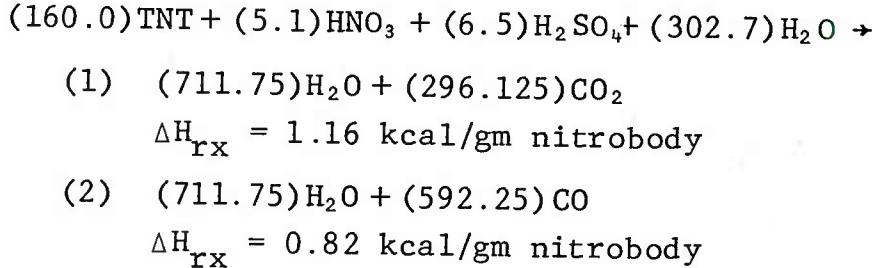


$$\Delta H_{rx} = 1.15 \text{ kcal/gm nitrobody}$$

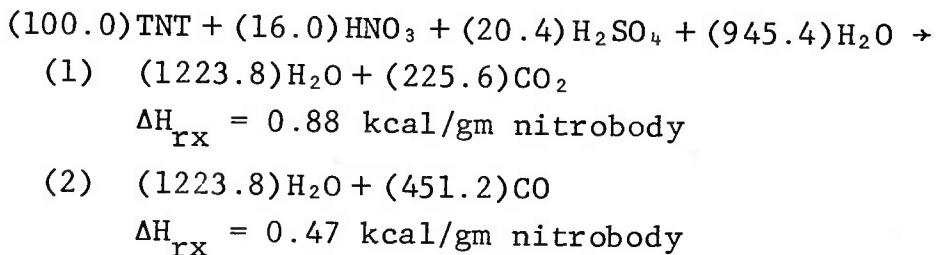
Test series 2 and 3 (stoichiometrically identical)
(old nitrator 6 and separator 6)



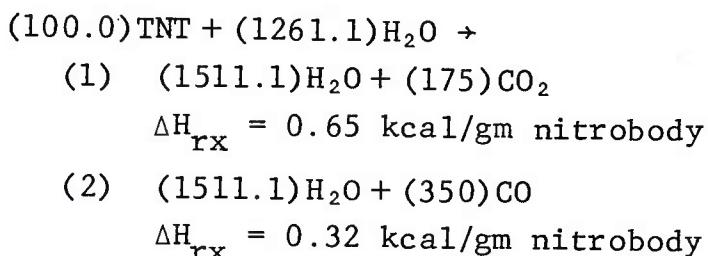
Test series 4 (acid wash tank, actual composition in full-scale system)



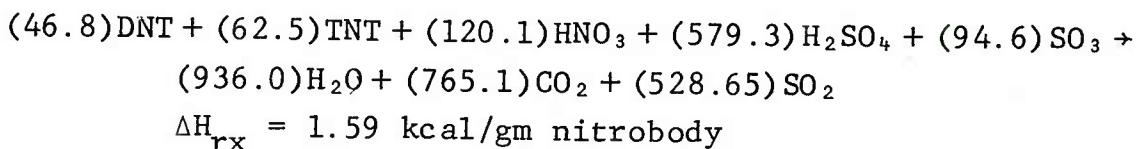
Test series 4 (acid wash tank, dilute composition tested)



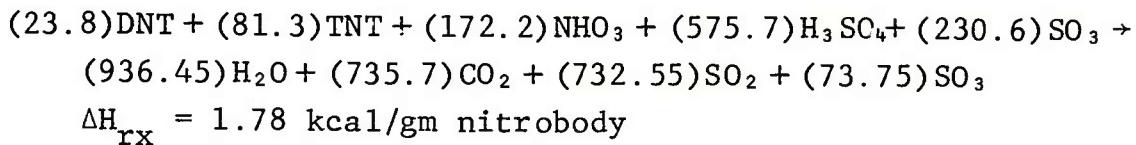
Test series 5 (sellite wash tank)



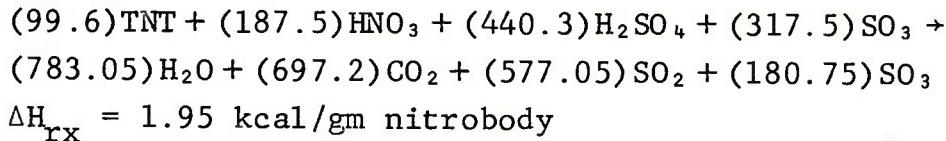
Test series 6 (new nitrator 4)



Test series 7 (new nitrator 5, not tested)



Test series 8 (new nitrator 8)



These calculations can be summarized in table 26.

Table 26

Energy equivalencies^a (TNT equivalency-percent)

<u>Test series</u>	<u>Average CO/CO₂</u>	<u>Calculated values^b</u>	<u>Average of the two calculated energy equivalencies^c</u>
		<u>CO₂ only</u>	<u>calculated</u>
1	126	146	136
2	178	178	178
3	178	178	178
4	92 (based on real system)	107	100
4	62 (based on test mixture)	81	72
5	44	60	52
6	147	147	147
7	165	165	165
8	181	181	181

^a Energy equivalency is derived by dividing the calculated heat of reaction of the mixture by 1.08 kcal/gm for solid high density TNT.

^b Estimates were made based on all carbon being oxidized to CO₂ with excess carbon remaining as carbon (CO₂ column) and based on carbon oxidized to CO first. The average of the two estimates is listed in the first of the two columns.

^c These average values are used in airblast output predictions.

The energy output from 22.7 kg (50 lb) nitrobody in the various test series can be greater or lesser than the energy output from the detonation of the nitrobody alone. In the case of oxidizer rich explosives; e.g., PETN and nitro-glycerine, a fuel additive will enhance the overall energy output of the detonation. In addition, an additive of water, which in this analysis only abstracted energy by being converted from a liquid to a gas (heat of vaporization) in addition to being heated, can in actuality add to the effective energy output in terms of crater size and mass movement due to its volume increase and consequent effect on pressure-time factors. This effect, as well as other factors that effect pressure time, or impulse effects, due to extended reaction zones and times and the variations caused in product gas densities and pressures (at the cost of reduced temperatures, perhaps) have not been considered.

5.1.3 Energy Equivalencies Used to Correlate Experimental Data

The energy equivalencies computed in section 5.1.2 and the technique described in section 5.1.1 have been used to condense the experimental data for all the cylindrical process components which detonated onto a common 100 percent TNT equivalent curve for peak overpressure and a common 100 percent TNT equivalent curve for scaled positive impulse. The experimental data for peak overpressure is presented in figure 66. The data correlate quite nicely using this technique. Also shown is the curve for a solid TNT cylinder (length to diameter ratio of 2). At large scaled distances, the solid TNT cylinder data converge with the process vessel data. In the near field, the TNT cylinder produces significantly higher peak overpressures. This near field divergence in the curves may be due to differences in source energy densities, detonation rates, internal geometries, etc. This difference in near field blast fields points to the conclusion that some testing must be done using similar chemical compositions and total geometry (internal and external) to those in the components of interest. The present state of knowledge does not quite allow one to go directly from tests using some standard material, such as solid TNT, to predict the total blast field produced by process chemicals which are quite different from solid TNT.

Figure 67 plots the data for scaled positive impulse condensed onto a single TNT equivalent curve. The correlation is not as good for impulse as it was for pressure, but it is adequate to define an average curve for the 100 percent equivalent case.

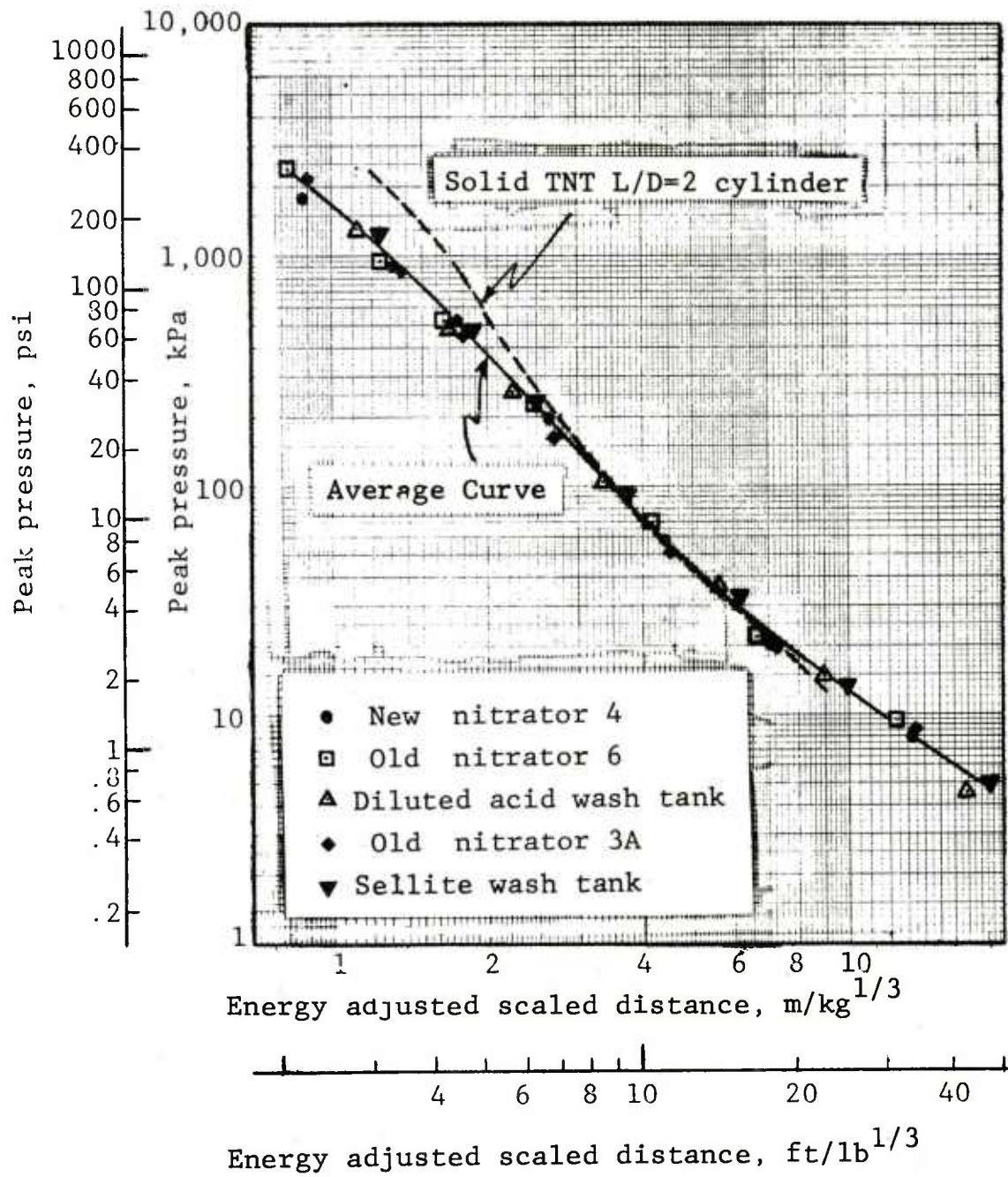


Fig 66 Correlation of peak overpressure data

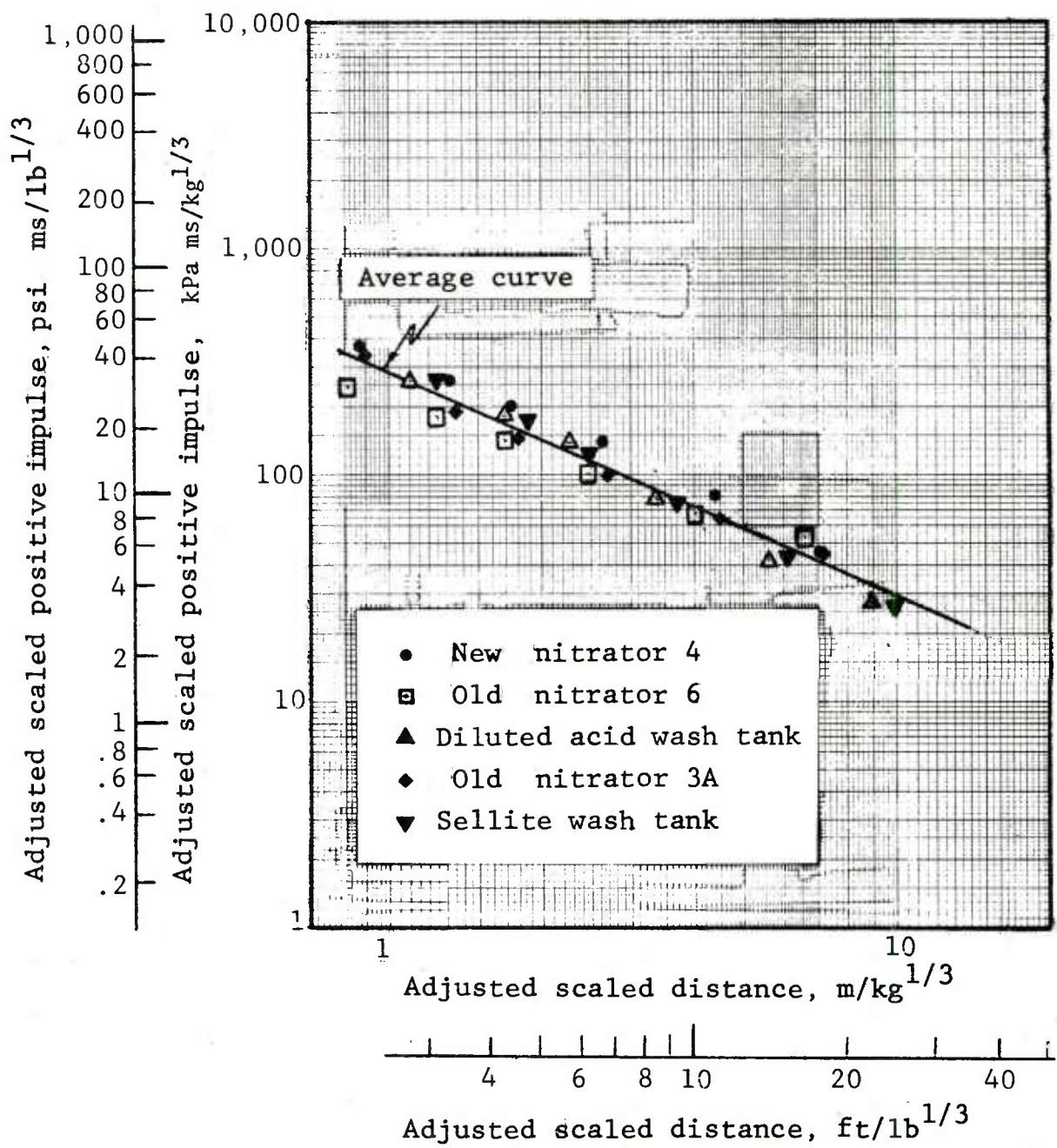


Fig 67 Correlation of impulse data based on energy equivalencies

5.1.4 Prediction of Acid Wash Tank Airblast Output

As discussed in section 5.1.1, once a TNT equivalent curve is obtained for peak overpressure and scaled positive impulse, one can work backward to obtain the curves for any of the process components using an inverse scaling factor equal to $1/f$, where f is defined in section 5.1.1. For the acid wash tank, the average energy equivalency happens to be 100 percent, as computed in section 5.1.2. Therefore, for this component, the 100 percent TNT equivalent curves for pressure and impulse (figures 66 and 67) are identical to the acid wash tank curves (i.e., $f=1$). All that remains for this system is computation of TNT equivalencies associated with peak overpressure and scaled positive impulse. These curves will not be constant valued at 100 percent because energy is not the only consideration. The configuration will strongly skew the resultant curves. Configuration effects include internal and external geometry, energy density, and detonation rate. The predicted equivalency curves for the actual (not diluted) acid wash tank compartment are presented in figure 68.

5.2 Initiation Sensitivity of the Process Vessels

During this experimental program, it was found that a full detonation is quite difficult to achieve in the continuous TNT process components which were tested. They were found to be quite insensitive to initiation using an explosive booster, and an explosive booster is the most severe initiation stimulus which can be used. Initiation using an explosive booster implies that an established detonation front can continue to propagate into the test material, whereas initiation with a less severe stimulus (i.e., fire, lesser impact, friction, etc.) requires that a detonation front be established within the test material. Detonations were obtained during this test program, but there were several indications that the process vessels were at or near the transition point for obtaining a full detonation. These observations are discussed.

5.2.1 Booster Size

The most obvious indication that the tests were near the threshold for detonation was that a very large booster size was required in all cases to initiate detonation. Test series 2 (old nitrator 6), test series 3 (old separator 6), and test series 6 (new nitrator 4) all included one shot with a 5 percent (percent of the nitrobody weight) booster which did not detonate, and subsequent use of 10 percent boosters all resulted in detonations.

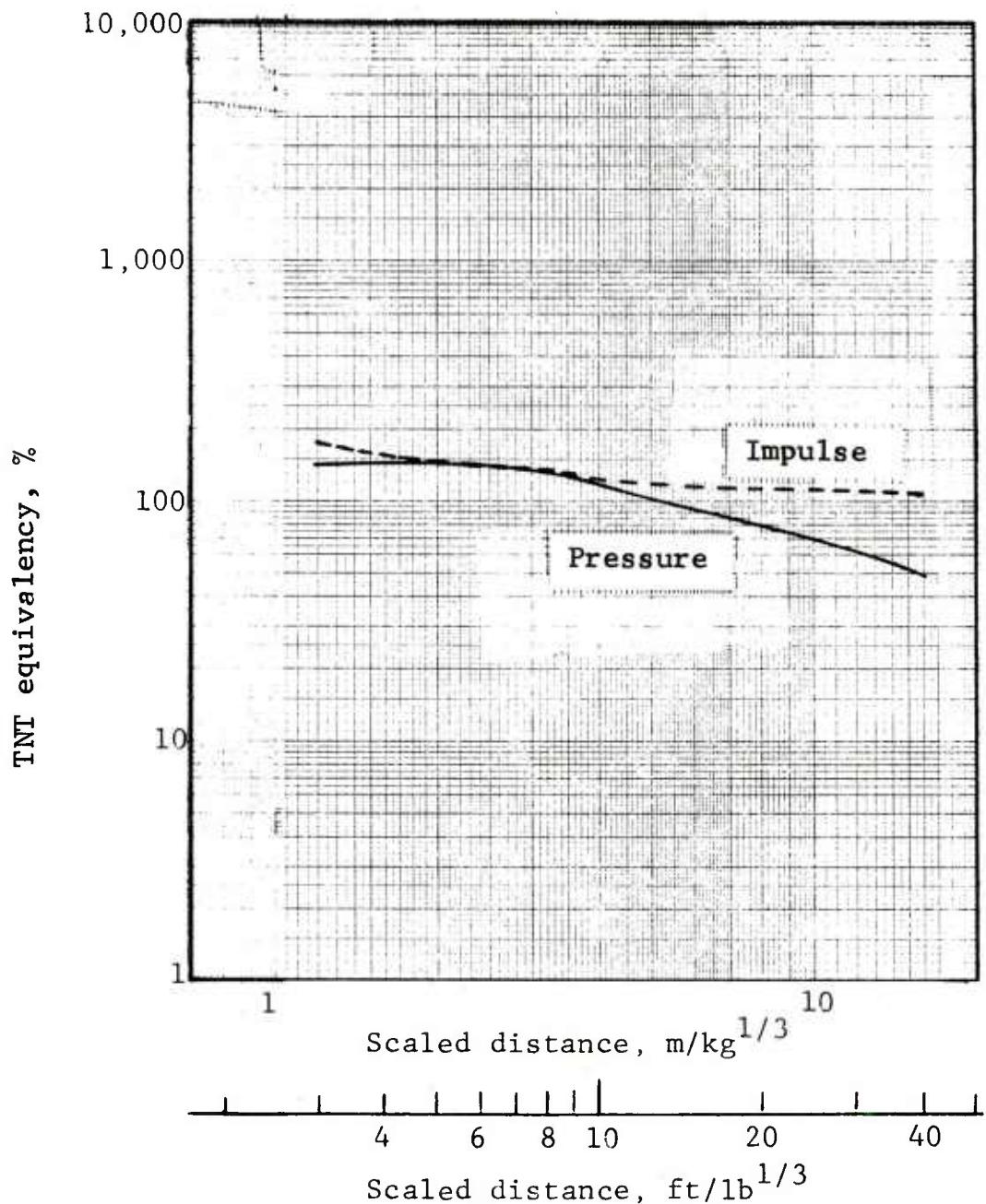


Fig 68 Acid wash tank compartment maximum envelope TNT equivalencies, predicted from the other test series

5.2.2 Test Results

In many cases, the test results presented in section 4 and appendix C showed that even when detonations occurred, the intensity of detonation varied within a test series. This was observed in peak overpressure and scaled positive impulse curves for several test series. Data points laid on separate curves, one above another, rather than scattered about some average curve. This was the reason that TNT equivalencies were derived based on maximum envelopes rather than a curve fit to all the data. The good correlation of the scaled data presented in section 5.1.3 indicates that at least one test in each series must have been at or very near to a full detonation, since the maximum envelopes appear to have been defined properly to give the good correlation. The detonation velocity data also showed a range of average values which in most cases corresponded to the ordering shown by the pressure and impulse curves.

5.2.3 Coil Confinement Effect

New nitrators 4 and 8 were quite similar in many respects to one another; however, nitrator 4 detonated and nitrator 8 could not be made to detonate even with a 15 percent booster size and with a scaleup in tank size to the 90.8 kg (200 lb) of nitrobody level. There were chemical composition differences between the two components:

Weight percent compositions used in tests

	<u>nitrator 4</u>	<u>nitrator 8</u>
DNT	9	0
TNT	15	21.90
HNO ₃	8	11.44
H ₂ SO ₄	60	41.80
SO ₃	8	24.60

These composition differences were not extreme. Both systems had about 22 to 24 percent nitrobody. Nitrator 8 had more fully oxidized nitrobody and more excess nitric acid to add oxygen during a reaction; nitrator 8 could have been expected to be more likely to initiate based on the composition differences.

The most distinct difference between the two components is in the coil design. Nitrator 4 has over twice the coil mass of nitrator 8 (by a factor of 2.34). This extreme difference in the mass of metal between the draft tube and the

outer tank wall probably explains why nitrator 4 detonated and nitrator 8 did not. The extra coil mass might be necessary to confine the developing detonation (not allow quick expansion of products) and result in the buildup of a detonation or prevent the decay of the booster detonation front. If it is possible to design process vessels to minimize such confinement, it might be feasible to eliminate the possibility of detonations altogether.

5.2.4 Size Scaling

Every explosive material has a critical size for transition to detonation. Critical size can be separated into a critical diameter and length. The critical diameter represents the size at which sufficient material is present to confine itself and cause a detonation to develop within a core region. Critical length represents the length of material necessary for a developing detonation to travel through before it can transition into a full detonation. The exact critical dimensions are functions of the type and size of the initiation stimulus. Based on the results presented in section 4, it appears that the tests were conducted near or on the transition to detonation. For this reason, larger tests were planned at the 90.8 kg (200 lb) size. Although the large-scale tests were not completed (only one nitrator 8 shot was accomplished), the analyses in section 5.1 indicate that size scaling was reached in at least one test of each series (i.e., the maximum envelopes were apparently defined by full detonations).

One nitrator 8 test was completed at the larger size. It did not detonate even at the large scale. Unfortunately, in sensitivity studies, a negative result is inconclusive. The large-scale nitrator 8 test was still only about one-seventh the size by volume of the full-scale system (about one-half the size by linear dimensions). It cannot be said with absolute certainty that a full-scale nitrator 8 will not detonate or that even the scaled system will not detonate if a larger booster is used. All that can be concluded is that it is difficult to initiate nitrator 8 and it appears likely that it would not detonate in a larger size.

5.2.5 Other Considerations

Several other factors probably have some influence on sensitivity. These were not investigated in this program but should be mentioned.

Trace chemicals (e.g., white compound) are present in actual TNT processing systems. Some are present in solutions and some precipitate out of solution and deposit in pipes and on tank walls. In the tests requiring a batch reaction (old nitrator 3A and new nitrator 4) an attempt was made to add realism by using crude DNT, extracted from the Joliet AAP continuous TNT line. This crude DNT certainly contained some of these trace compounds, but they were in dilute quantities. It is unlikely that the trace compounds would affect the airblast output but they may have some effect on sensitivity.

In the test procedures, a period of time was allowed for agitation of liquid TNT in the hot acid mixture to dissolve some of the TNT. The target mixing time was 1 hr, but in reality mixing time had to be kept flexible to compensate for any operational problems or adverse weather conditions. Mixing time varied in the tests between about 20 min and 3 hr. There was no apparent correlation between mixing duration and blast output in the results. It is possible that mixing time could have had an influence on sensitivity, but there is no solid basis for making this conclusion either.

It has already been mentioned that the coil mass may have an effect on sensitivity. Other internal geometry differences existed between components and may have had an influence on sensitivity.

5.3 Conclusions

Throughout this report opinions have been given and conclusions noted whenever it was believed appropriate. Here some of the more significant conclusions and comments are summarized:

- The presence of nitric acid in the chemical mixture contributes oxygen to increase airblast output if a detonation occurs. The presence of water (such as in the sellite wash tank) removes energy from the system in the form of steam.
- All the systems tested were quite insensitive to initiation. A 5 percent booster size was inadequate in all cases, whereas a 10 percent booster generally was sufficient.
- New nitrator 8 did not detonate in any test, even using a 15 percent booster and even at the 90.8 kg (200 lb) nitrobody size. This indicates that nitrator 8 is insensitive to initiation stimuli but does not prove that the system cannot detonate in a full-scale process plant.

- Comparison of the new nitrator 8 test results with the new nitrator 4 results indicates that the decreased coil mass probably prevented nitrator 8 from detonating. Decreasing the confinement provided by the coils may be a good method of reducing the possibility of detonation in process vessels.
- Since nitrator 8 did not detonate in tests which were completed but possibly could detonate in the full-scale, the airblast output for nitrator 8 presented in this report should not be used as a design basis.
- The small-scale tests were at or near the detonation threshold. It appears that at least one test in each series did achieve a full detonation, but completion of the planned large-scale tests would be desirable to verify that size scaling was reached.

RECOMMENDATION

The TNT equivalency of pressure and impulse values determined from this test series should be used in the structural design of protective facilities.

6. REFERENCES

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APPENDIX A

PRESSURE AND IMPULSE MEASURING SYSTEMS

Pressure-time functions were monitored at locations as previously described. The pressure-time signals were integrated to produce impulse-time functions. Data signals were recorded on magnetic tape and reproduced on an oscillograph recorder. The following subsections contain a description of the instrumentation equipment, calibration technique and computational procedure employed on the test program.

A.1 Pressure Measuring Systems

Pressure-time functions are measured as the shock wave traverses the instrumentation stations along the blast lines. The shock wave is characterized by measuring station, peak overpressure, positive phase duration, and positive phase impulse.

At measuring stations near the charge or test item, the pressure time profile is characterized by high peak overpressures and short positive durations. Piezoelectric type transducers were used at those locations to provide the required dynamic pressure range and high frequency response. Conversely, the far field pressure-time profiles are characterized by low overpressure and relatively long positive durations. Capacitance type transducers were used at these locations to provide the required resolution and DC response.

The piezoelectric transducers employed quartz crystal as their sensing element. Two types of units were employed; the PCB Piezoelectronics Inc. (PCB) type 113A24 and the Kistler Instrument Corp. (KIC) type 603A. The PCB type 113A24 has a built-in amplifier. The pressure range is 1000 psi and the rise time is about 1 μ sec. The pressure range of the KIC 603A is 3000 psi. In the present configuration a voltage-follower amplifier, PCB 401A, is used with the unit. The addition of the voltage-follower provides operational benefits; it does however limit the pressure range of the system to about 350 psi. The rise time for the system is 1 μ sec.

A constant current power supply (PCB series 483A) is used to supply power to the built-in amplifiers. The signal output is connected to the cal-input of a KIC model 566 charge amplifier. The charge amplifier provides a convenient means for setting the system output levels for the various test requirements.

The capacitance type transducers employed on the test program were 5, 10, 20 and 40 psig. The frequency response for these units is normally DC to 10 kHz.

The PRP measuring system employs amplitude modulated r-f carrier techniques. The diaphragm of the transducer, in conjunction with an insulated stationary electrode, forms an electrical capacitor. The pressure to be measured is applied to the diaphragm, causing a change in capacitance proportional to the applied pressure. The transducer capacitance and a built-in inductance form a tuned radiofrequency circuit. The tuned circuit is line-coupled, by means of a low impedance cable, to a Dynagage system consisting of an oscillator-detector circuit and a cathode-follower amplifier. The changes in capacitance produce changes in the diode detector impedance, and thereby produce a signal voltage proportional to the applied pressure.

A.2 Transducer Mounting Adapters

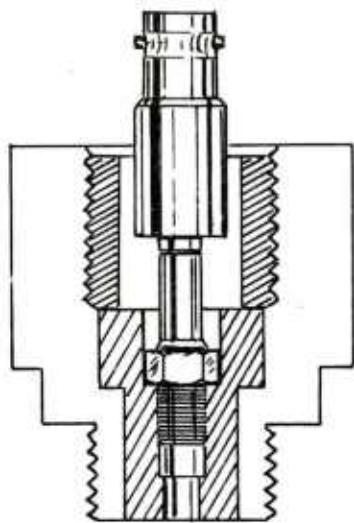
The transducer mounting adapters are illustrated in figure A.1. The piezoelectric transducers were installed in electrical insulated mounting adapters. Teflon seal rings were placed around the small diameter of the transducer to provide a pressure seal. The transducer is positioned such that its diaphragm is flush mounted with the face of the mounting adapter. Once assembled, the transducer is enclosed within the mounting adapter by using RTV-615 silicone potting compound.

The dimensions of the mounting adapters used for these gages are identical to those designed for the PRP type 752A transducers. Accordingly, transducer assignments and subsequent changes at the various gage locations can be implemented in a timely manner.

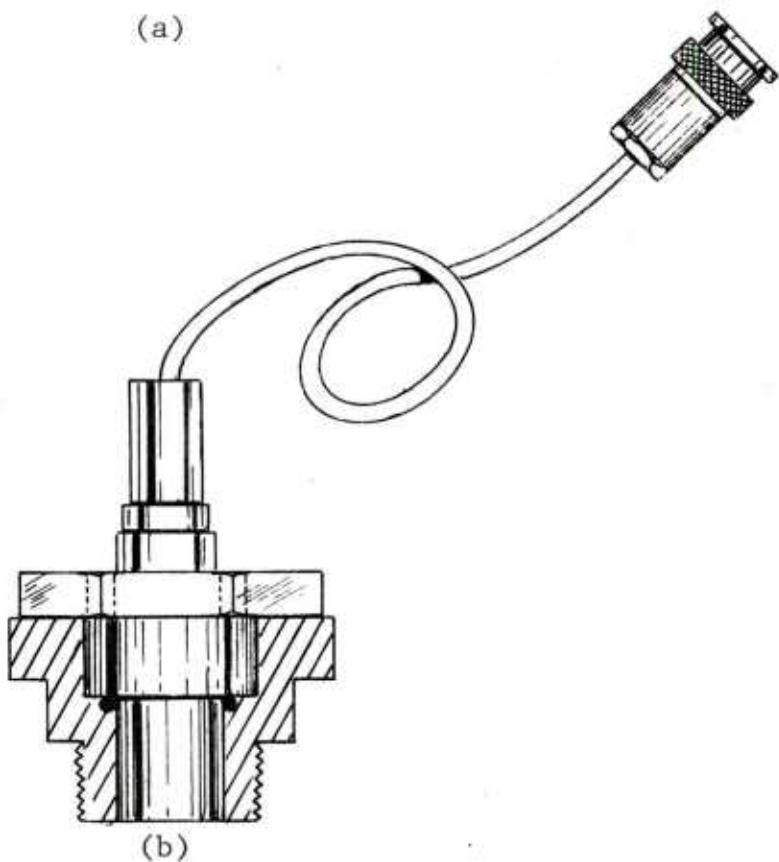
The PRP type 752A transducers were removed from their water-cooled flame shields and placed in an electrical insulated mounting adapter. The adapter was designed to provide flush mounting of the diaphragm. The electrical insulation material was used to break ground loops, thus reducing interference caused by stray pickup and intercarrier beats.

A.3 Calibration Procedures

The purpose of the calibration series is to establish the sensitivity factor for each pressure measuring system. The mounted transducer, transmission cable and signal conditioner are calibrated as a system.



(a)



(b)

Fig A.1 Transducer mounting adapter for the (a) KIC 603A and (b) the PRP 752A

The transducers, in turn, were placed in the expansion chamber of the calibration fixture. The calibration fixture consists of an expansion chamber with a volume less than 2 cu inches and a compression chamber with a volume of 380 cu inches. The chambers are separated by an electrically operated solenoid valve. The pressure in the compression chamber is monitored with a pressure transfer standard (Seegers 55-2455A) for calibration pressures in the range 20 to 300 psig. A mercury manometer is used to monitor pressures below this range.

When the solenoid valve is actuated, the transducer is subjected to a pressure rise. The pressure rise-time in the expansion chamber is less than 2 msec. The applied pressure causes a voltage to be generated at the output of the signal conditioner.

The piezoelectric transducer sensitivity factor (K_i) is the output voltage of the charge amplifier (V), divided by the charge amplifier setting (S) and the applied pressure P

$$K_i = \frac{V}{S \cdot P} \text{ (pcb/psi)} \quad (1)$$

Similarly, the sensitivity factor for the Photocon Research systems is the output voltage from the Dynagage (V) divided by the applied pressure P.

$$K_i = \frac{V}{P} \text{ (Volt/psi)} \quad (2)$$

The systems are calibrated at five pressure levels in the pressure range of interest. The quantity \bar{K} is the arithmetic mean of the value of K_i as determined for each calibration pressure level.

The rms deviation (r) for \bar{K} was determined by the relationship

$$r = \frac{1}{N} \left[\sum_{i=1}^N (\bar{K} - K_i)^2 \right]^{1/2} \quad (3)$$

The percent deviation was determined by the relationship:

$$r_{100} = \frac{2r}{\bar{K}} \times 100 \text{ (\%)} \quad (4)$$

Using a factor of 2 in the numerator of equation (4) gives a confidence level of 95.5 percent.

The calibration data are used to access the time constants of the piezoelectric transducers. A storage oscilloscope is used to record a pressure-time trace for a calibration test. The time constant (RC) is evaluated at a time(t) by the relationship:

$$RC = -t/\ln \frac{V_t}{V_o} \quad (5)$$

where V_t and V_o are the voltage levels at time t and t_o respectively.

A.4 Field Installation

The transducers were installed in steel mounting plates on the centerlines of two 75-ft long by 10-ft wide concrete blast pads. Pressure measurements were made at six stations on the east gage lines and at seven positions on the north gage line. The transmission lines were run, in conduit in the nearfield and above ground in the farfield, to the instrumentation trailer. The instrumentation trailer housed the signal conditioning equipment, monitor and control circuitry and recording equipment.

A.5 Signal Conditioning and Recording Instruments

The data signals from the pressure measuring systems were fed to the calibration monitor unit. This unit is used to monitor each gage line and assess the pretest condition of the pressure measuring systems. This unit is also used to provide an electrical calibration signal which is recorded on each data track immediately preceding each test run. The electrical calibration signal is a voltage simulation of a predetermined pressure or impulse level. This signal is used in data reduction as discussed in a later section.

Hewlett Packart (HP) model 8875A differential amplifiers were used to provide a voltage gain and thus condition the signal for magnetic tape recording. The pressure data signals were recorded on a Sangamo Sabre III instrumentation tape recorder. This unit is equipped with 13 FM recording tracks for data recording, and a single channel of direct record for time base signals. The tape recorder conforms to specifications for the IRIG wideband group 1 (Document 106-71).

A.6 Pressure Impulse Measurements

The pressure impulse is defined as the area under the pressure time history

$$I(t) = \int_{t_0}^t P(t) dt \quad (6)$$

where P is the pressure and t is the time.

The signal voltage at the output of the model 8875A amplifier is an electrical analog of the pressure-time history. This signal was used as input to a Tektronix type 0 operational amplifier, where the electrical integration was performed. The integrated signal was amplified and in turn, recorded on a CP100 magnetic tape recorder. This recorder conforms to specifications for the IRIG intermediate band.

A.7 Data Reproduction

Oscillograph reproductions of the magnetic tape recordings were made by employing Consolidated Electrodynamics Corp. (CEC) type 1-172 driver amplifiers to drive a CEC type 5-124 recording oscillograph. The oscillograph was equipped with CEC type 7-363 galvanometers.

The pressure data were recorded at a tape speed of 60 ips and reproduced at a tape speed of 1-7/8 ips, resulting in a frequency division of 32. The oscillograph paper speed was 32 ips. For these conditions, the oscillograph has a horizontal resolution of 976 μ sec/inch and an effective frequency response from DC to 40 kHz, referred to real time.

The pressure impulse data were also recorded at a tape speed of 60 ips and reproduced at a tape speed of 1-7/8. The effective frequency response is DC to 30 kHz, referred to real time.

A.8 Block Diagram

A simplified block diagram of the pressure and impulse instrumentation system is shown as figure A2. Two data channels are shown; one to illustrate the piezoelectric measuring system and the second to show the capacitance type pressure measuring system. In the test program, six piezoelectric type systems and seven capacitance systems were employed.

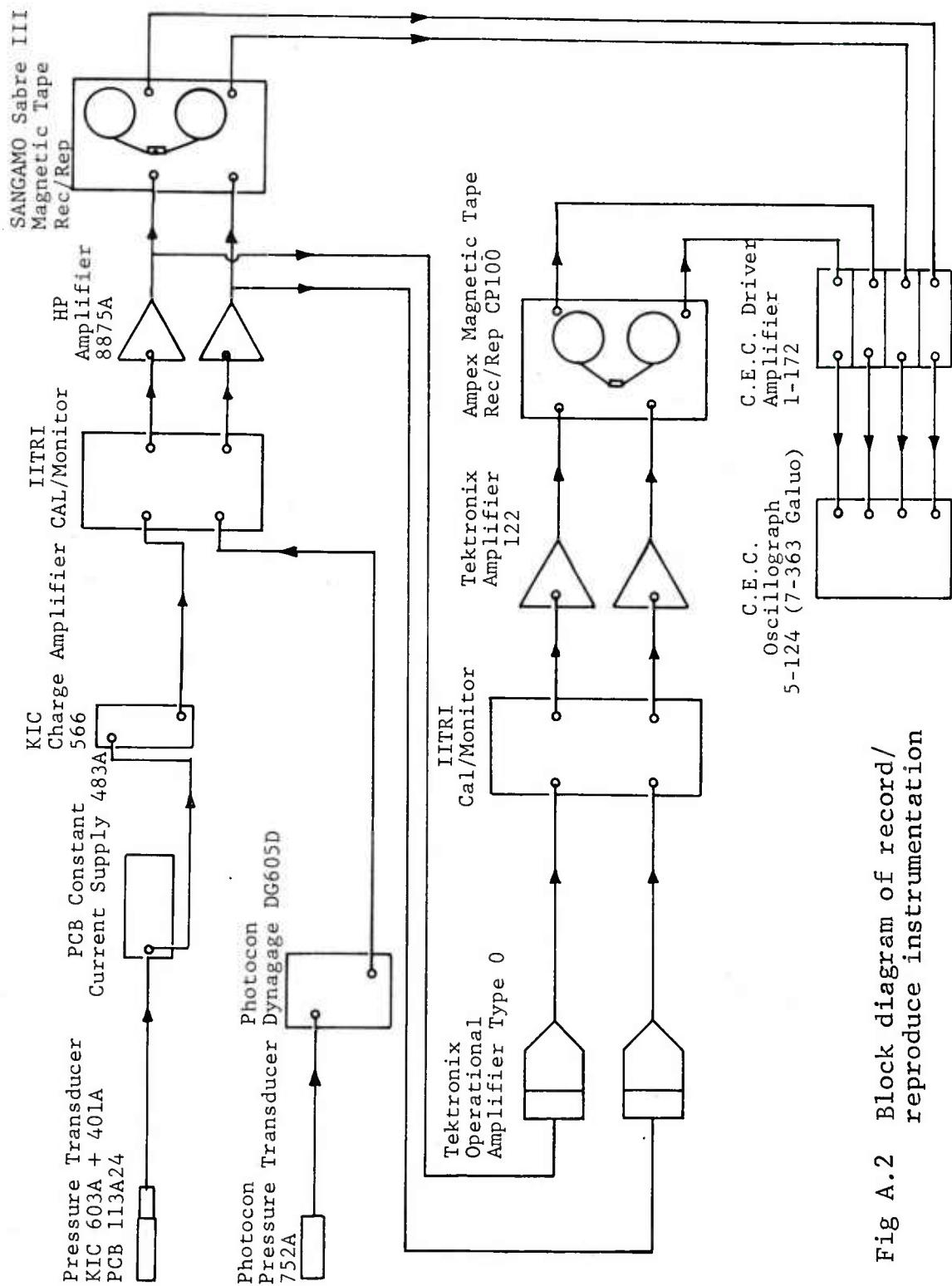


Fig A.2 Block diagram of record/reproduce instrumentation

A.9 Computational Procedure

This subsection contains the equations used to determine the relationship between signal amplitude on the oscilloscope recording and applied pressure and impulse. The symbols and units are:

$p(t)$ = applied pressure (psi)
 K = sensitivity factor of pressure sensing system (volts/psi) or (Pcb/psi)
 $I(t)$ = pressure impulse (psi-sec)
 t_o = initial time (sec)
 t_d = time of positive duration of the pressure pulse (sec)
 E_{c1} = calibration voltage for the pressure channel (volts)
 E_{c2} = calibration voltage for the impulse channel (volts)
 D_{c1} = deflection of trace due to pressure calibration signal (inch)
 D_{c2} = deflection of trace due to impulse calibration signal (inch)
 $D_{t1}(t)$ = deflection of trace due to the applied pressure (inch)
 $D_{t2}(t)$ = deflection of trace due to the applied impulse (inch)
 A_1 = voltage gain of Sanborn 8875A amplifier
 A_2 = voltage gain of Tektronix 122 amplifier
 A_s = combined voltage gain of record/reproduce system and galvanometer sensitivity (inch/volt)

Figure A3 shows an illustration of an oscilloscope print of the experimental data. Those terms taken from the experimental data and used in the data reduction equations are identified.

The peak overpressure and maximum impulse are the important parameters determined from the recorded data. The general expression for determining $P(t)$ is determined in the following manner.

The deflection of the oscilloscope trace due to the calibration signal is

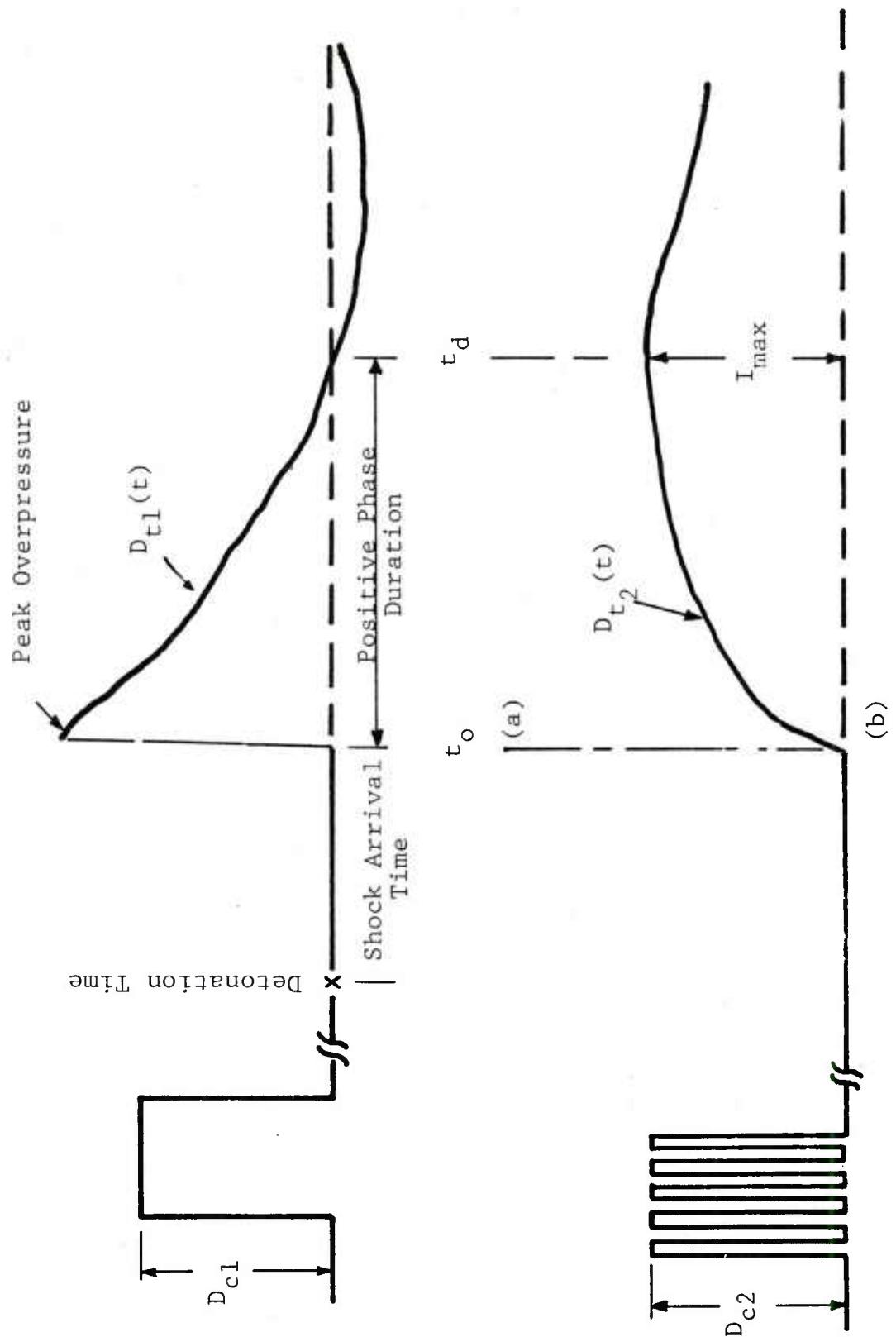


Fig A.3 Illustration of oscillograph print of (a) pressure versus time, and (b) impulse versus time.

$$D_{c1} = E_{c1} A_1 A_s \quad (7)$$

The deflection of the trace due to the applied pressure is

$$D_{t1}(t) = K P(t) A_1 A_s \quad (8)$$

Combining equations (7) and (8)

$$P(t) = \frac{E_{c1} D_{t1}(t)}{K D_{c1}} \quad (9)$$

The peak overpressure is the pressure determination at $t = t_0$ as indicated in figure A3.

The pressure impulse is determined by an analog integration of the pressure-time function. Referring to the block diagram (figure A2), and assuming the validity of the ideal gain of the generalized operational amplifier

$$\frac{E_o}{E_i} = - \frac{Z_o}{Z_i} \quad (10)$$

where E_i and E_o are the input and output voltages of the operational amplifier respectively, and Z_i and Z_o are the input and feedback impedances.

For the integrator configuration

$$Z_i = R \text{ and } Z_o = \frac{1}{Cp} \quad (11)$$

where p is the operator, $\frac{d}{dt}$

The gain expression in terms of the circuit parameters is

$$E_o = - \frac{Z_o}{Z_i} E_i = - \frac{E_i}{RCp} = - \frac{1}{RC} \int E_i dt \quad (12)$$

Writing the gain expression in terms of the applied pressure

$$E_o = \frac{A_1 K}{RC} \int_{t_0}^t P(t) dt \quad (13)$$

Noting that $E_o A_2 A_s = D_{t2}(t)$

$$D_{t2}(t) = \frac{A_1 A_2 A_s K}{RC} \int_{t_o}^t P(t) dt = \frac{A_1 A_2 A_s K}{RC} I(t) \quad (14)$$

The deflection of the trace due to the calibration voltage is

$$D_{c2} = E_{c2} A_2 A_s \quad (15)$$

Combining the expressions for $D_{t2}(t)$ and D_{c2}

$$I(t) = \frac{RC E_{c2} D_{t2}(t)}{A_1 K D_{c2}} \quad (16)$$

The maximum pressure impulse is evaluated at the end of the positive phase duration, t_d , of the pressure pulse.

$$I_{\max} = \frac{RC E_{c2} D_{t2}(t_d)}{A_1 K D_{c2}} \quad (17)$$



APPENDIX B

TNT EQUIVALENCY CALCULATION PROCEDURE

B.1 Computational Procedure

The computational procedure used to obtain TNT equivalencies is discussed in this appendix. TNT equivalency for pressure is defined as the ratio of TNT weight to test explosive weight that will give the same peak overpressure at the same radial distance from each charge. Similarly, the TNT equivalency for impulse is defined as the ratio of charge weights that will give the same positive impulse at the same radial distances. The standard TNT charge used for comparison is a hemisphere placed on a rigid ground surface. Since the booster used to detonate the test explosive, propellant, or pyrotechnic may be of the order of 10 percent of the test material weight it is necessary to account for its contribution to the explosive output (i.e., peak pressure and impulse).

The symbols used in this discussion are:

W	weight, kg
R	radial distance from charge, m
$\lambda = R/W^{1/3}$	scaled distance, m/kg
P	peak overpressures, kPa
I	positive impulse, kPa-msec
E	TNT equivalency, percent

These subscripts and superscripts are self-explanatory when applied to the above symbols:

S	test sample
B	booster
TNT	TNT explosive
I	impulse
P	pressure
*	quantity is not adjusted for booster weight
TOT	total charge weight, booster plus sample

Pressure equivalency is determined by first measuring the quantities W_S , R , and P_{SB} . Where P_{SB} is the peak pressure measured when the sample is detonated with a C-4 booster. It includes an energy contribution from both C-4 and sample.

One must first approximate an equivalent booster weight, in terms of the charge sample weight, so that its weight can be included in the total charge weight. The approximation is found by obtaining λ_{TNT} , from figure B1, for $P_{SB} = P_{TNT}$.

The first approximation for TNT pressure equivalency is then

$$E_p^* = W_{TNT}/W_S = (\lambda_S/\lambda_{TNT})^3$$

where

$$\lambda_S = R/W_S^{1/3}$$

and

$$\lambda_{TNT} = R/W_{TNT}^{1/3}$$

Since the pressures are to be equal at the same radial distance, the R 's cancel in the above equation. One applies this approximated equivalency, E_p^* , to the weight of the booster to obtain the total charge weight.

$$W_{TOT} = W_S + (1/E_p^*) W_B (1.25)$$

A factor of 1.25 is applied to the C-4 booster weight to obtain its equivalent TNT weight.

A new λ is now computed from

$$\lambda_{TOT} = R/W_{TOT}^{1/3}$$

and a corrected pressure TNT equivalency is computed.

$$E_p = W_{TNT}/W_{TOT} = (\lambda_{TOT}/\lambda_{TNT})^3$$

The P subscript indicates a scaled distance for pressure and is computed from the revised sample weight. This iterative process can be repeated using the revised value of E_p to recompute the weight of the booster in terms of the sample

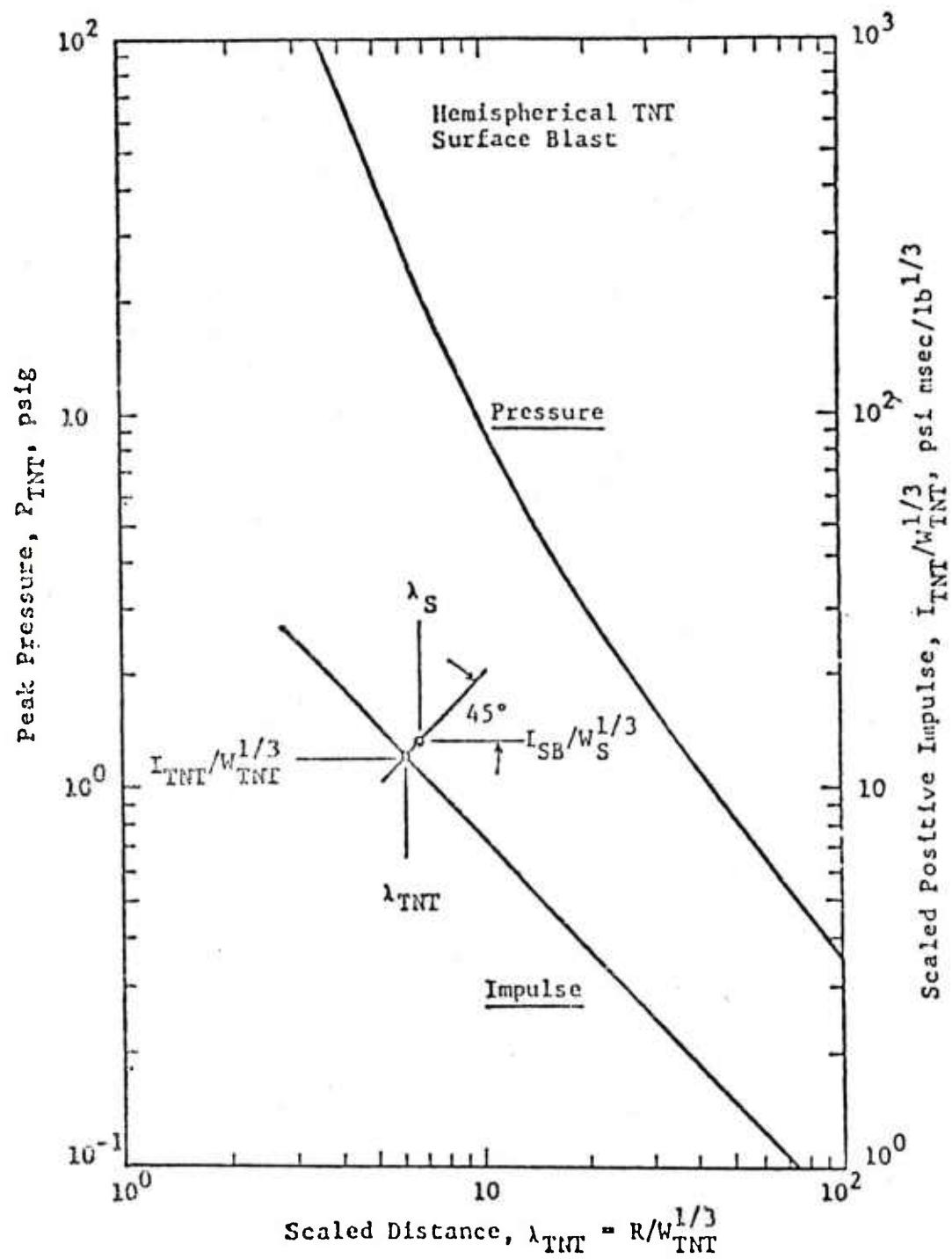


Fig B.1 TNT pressure and impulse



APPENDIX C

REACTION FRONT VELOCITY DATA

During this program, each test was instrumented with at least two "detonation" velocity probes. For the small-scale tests -- 22.7 kg (50 lb) of nitrobody -- fiber optic probes and ion probes were used. For the larger scale tests, the fiber optic probes were replaced by continuous probes and shock pressure-time of arrival probes as described in section 2. In all cases, the operation of the probes was verified using a conventional explosive with known detonation velocity prior to using the system in the mock TNT process components. Nonetheless, considerable difficulties were encountered with the various probes in the "nitrobody" experiments, particularly with the fiber optic probes. Generally, the signals were quite noisy and difficult to interpret.

In this appendix, the data, which were interpretable is presented. Table C1 summarizes the results. The average reaction front velocity was computed for readings within the TNT process component. The first probe reading was influenced strongly by the C-4 explosive booster and was not included in the average*. The following weighted averaging relation was used:

$$D_{ave} = \frac{\sum_{i=2}^n \{D_{i \rightarrow (i-1)}\} \times \{L_{i \rightarrow (i-1)}\}}{\sum_{i=2}^n \{L_{i \rightarrow (i-1)}\}}$$

where n is the number of probes within the process tank, $D_{i \rightarrow (i-1)}$ is the average detonation velocity computed between probes i and $i-1$, and $L_{i \rightarrow (i-1)}$ is the distance between probes i and $i-1$. Probe 0 was located in the explosive booster and was not included in this averaging technique.

* In some shots, when data was limited, the average velocity between probe 0 located in the explosive booster and one other probe was used in the estimation of D_{ave} . These cases are shown with an * in table C1.

Table C.1
Summary of reaction front velocity data

	Shot	Average reaction front velocity m/s	Booster weight (% of nitrobody present)	Special considerations
Nitrator 3A (test series 1)	1	4722*	10	Detonation
	2	----	10	Detonation
	3	----	10	Detonation
	4	----	10	Detonation
Nitrator 6 (test series 2)	1	----	10	Detonation
	2	6758	10	Detonation
	3	4569*	10	Detonation
	4	6132*	10	Detonation
Separator 6 (test series 3)	1	1022	5	Apparently did not detonate
	2	2261*	10	Apparently did not detonate
	3	5997	10	Full detonation
	4	7082	10	Full detonation (largest crater size)
Acid Wash Tank (test series 4)	1	----	10	Some parts found
	2	6808	10	Some parts found
	3	----	15	Some parts found
	4	----	15	Some parts found
Sellite Wash Tank (test series 5)	1	2815	10	Apparent detonation (some parts found)
	2	3439	10	Apparent detonation
	3	2989	10	Apparent detonation
	4	2855	15	Apparent detonation
Nitrator 4 (test series 6)	1	5558	10	Lowest output detonation of series
	2	----	5	Did not detonate
	3	5793	10	High output detonation
	4	7040	10	Highest output detonation of series
Nitrator 8 (test series 8)	1	3209*	10	Did not detonate
	2	2675	15	Did not detonate
	3	2135	15	Did not detonate
TNT cylinder		6539		6640 m/s published for cast TNT

* Average velocity computed using probe located in booster in addition to other probes.

The data obtained for nitrator 3A is presented in figure C1. Shot 1 was the only test with distinguishable signals. The data from this test series were quite limited and should not be considered conclusive.

More data were available for nitrator 6. Although there is considerable scatter in the data, a general trend appears to be present. The reaction front velocity apparently rises from a value below 6000 m/sec to somewhere above 7000 m/sec (22,960 fps) during the traverse of the reactor.

Figure C3 presents the separator 6 data. In this series, shots 1 and 2 did not detonate whereas shots 3 and 4 exhibit the highest apparent output of all the series. The data were quite consistent for the detonation and nondetonation cases and is probably reliable.

Only one acid wash tank test produced distinguishable data. The chemical mixture in these tests was incorrect -- much too dilute in notroboby. The airblast output for shot 2 (the only shot with reaction front velocity data) was quite low and some fragments were found indicating that detonation did not occur. The high reaction front velocity indicated by the data in figure C4 does not support the other data and observations. Therefore, this reaction front velocity data is considered to be questionable.

The sellite wash tank series is presented in figure C5. All four tests produced similar data indicating that the detonation (or reaction front) velocity is very likely to be about 3000 m/sec (9840 fps).

The data presented in figure C6 for nitrator 4 was generally fairly good. With the exception of one data point, shots 1 and 3 showed the same trend -- a rise from about 5000 m/sec (16,400 fps) to about 6000 to 7000 m/sec (19,680 to 22,960 fps). Shot 4 showed an early rise to about 9000 m/sec (29,520 fps) and then a drop to nearly the same final value as the other two shots presented. The data for shot 4 were not good quality and should not be considered to be reliable.

Data for nitrator 8 is shown in figure C7. The data were fairly good and consistent between the shots. The low values of reaction front velocity corresponds to the lack of detonation observed from the other data.

A 19.1 kg (42 lb) TNT cylinder was detonated to closely compare airblast output, crater size, whitness plate damage and detonation velocity with the various TNT process vessels tested. Detonation velocity for this test is shown in figure C8. The signals for this test were quite clean and distinct. Although the fiber optic and ion probes do not agree well in the initial reading, the trend shown by the two sets of data is quite good. There is a general drop from the C-4 booster detonation velocity to the value published for cast TNT* during the propagation of the detonation front.

*"Engineering Design Handbook, Explosives Series Properties of Explosives of Military Interest," Army Materiel Command Pamphlet AMCP 706-77.

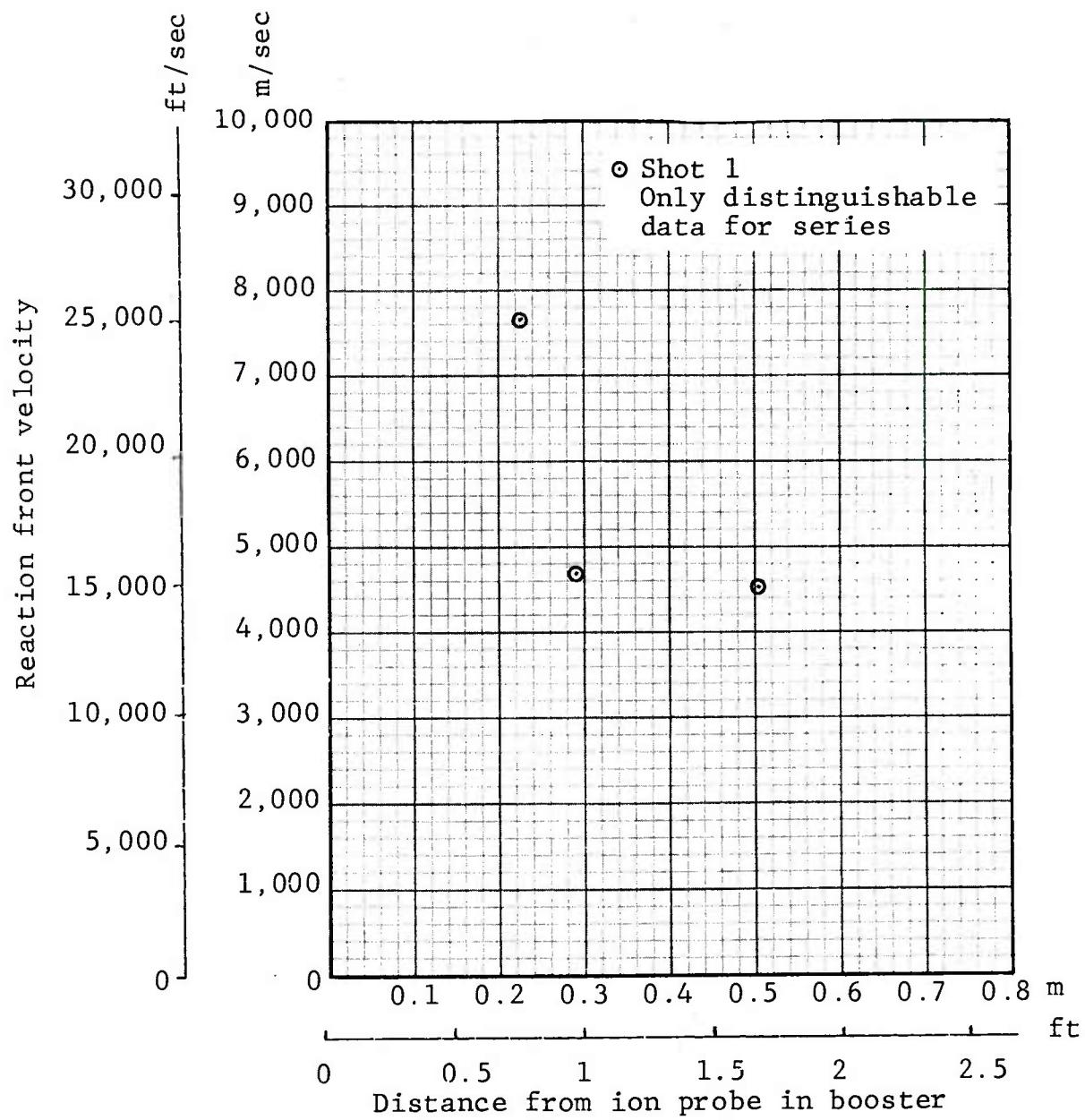


Fig C.1 Test series 1, nitrator 3A, reaction front velocity data

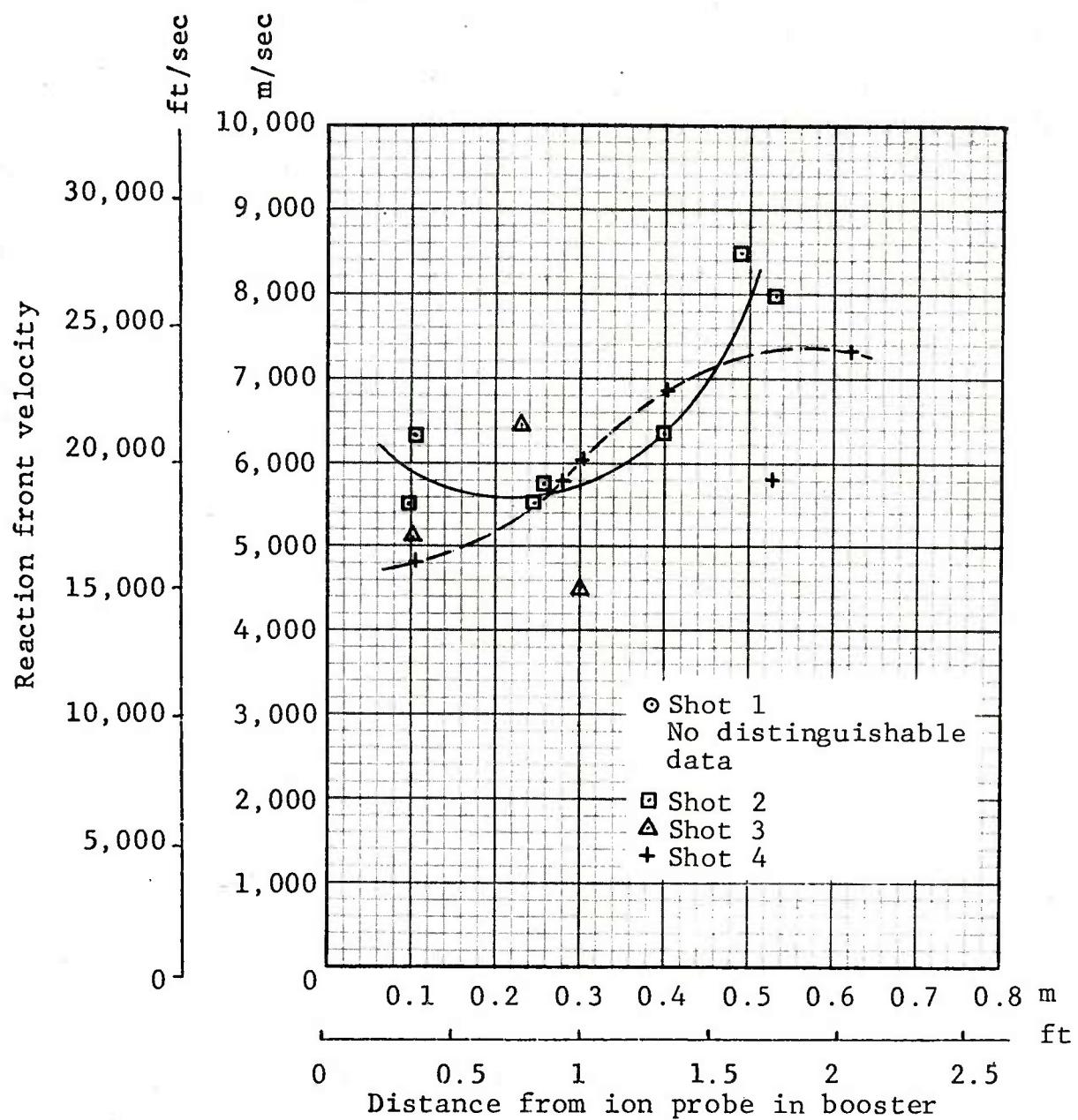


Fig C.2 Test series 2, nitrator 6, reaction front velocity data

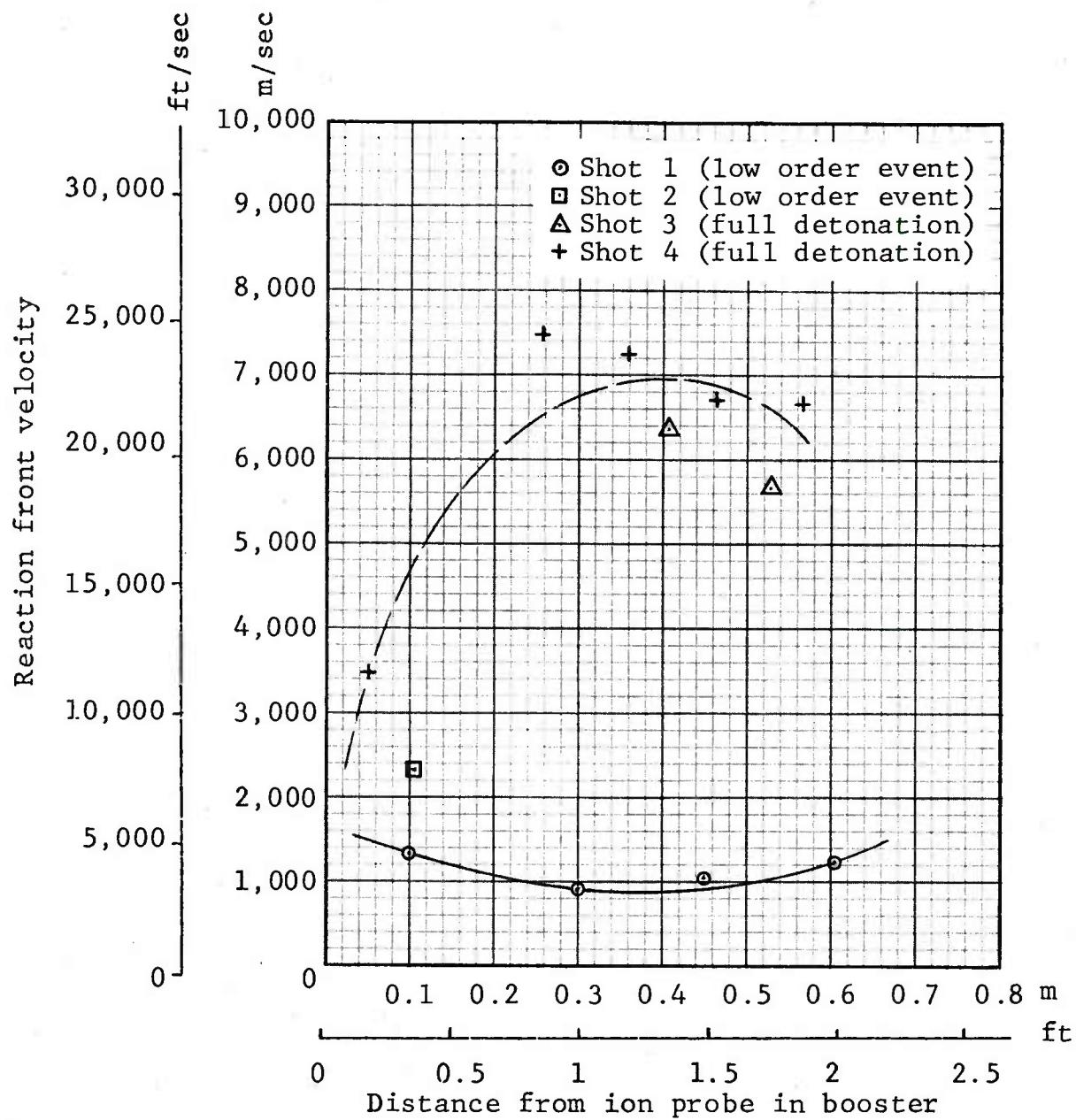


Fig C.3 Test series 3, separator 6, reaction front velocity data

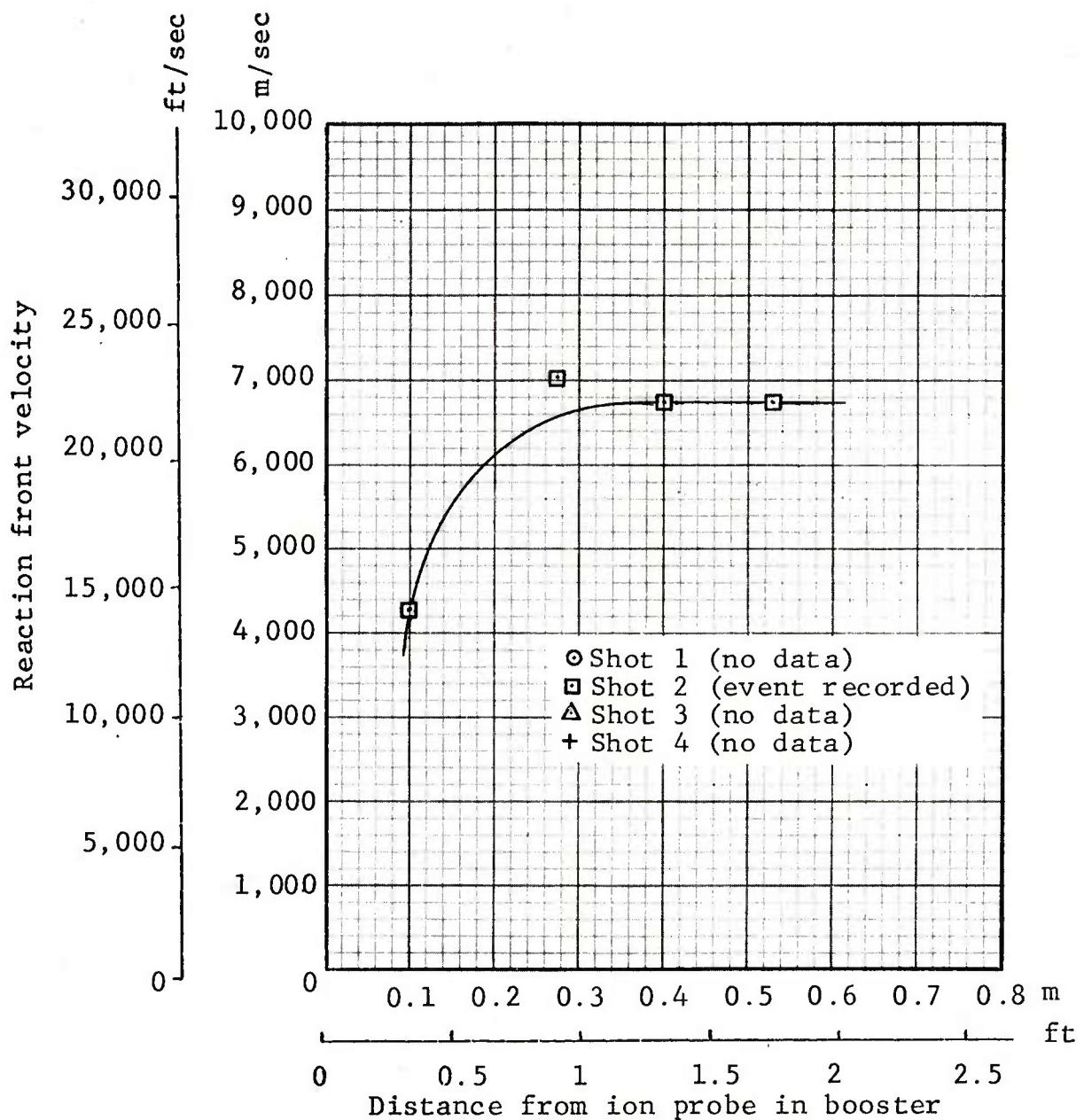


Fig C.4 Test series 4, acid wash tank, reaction front velocity data (dilute mixture used)

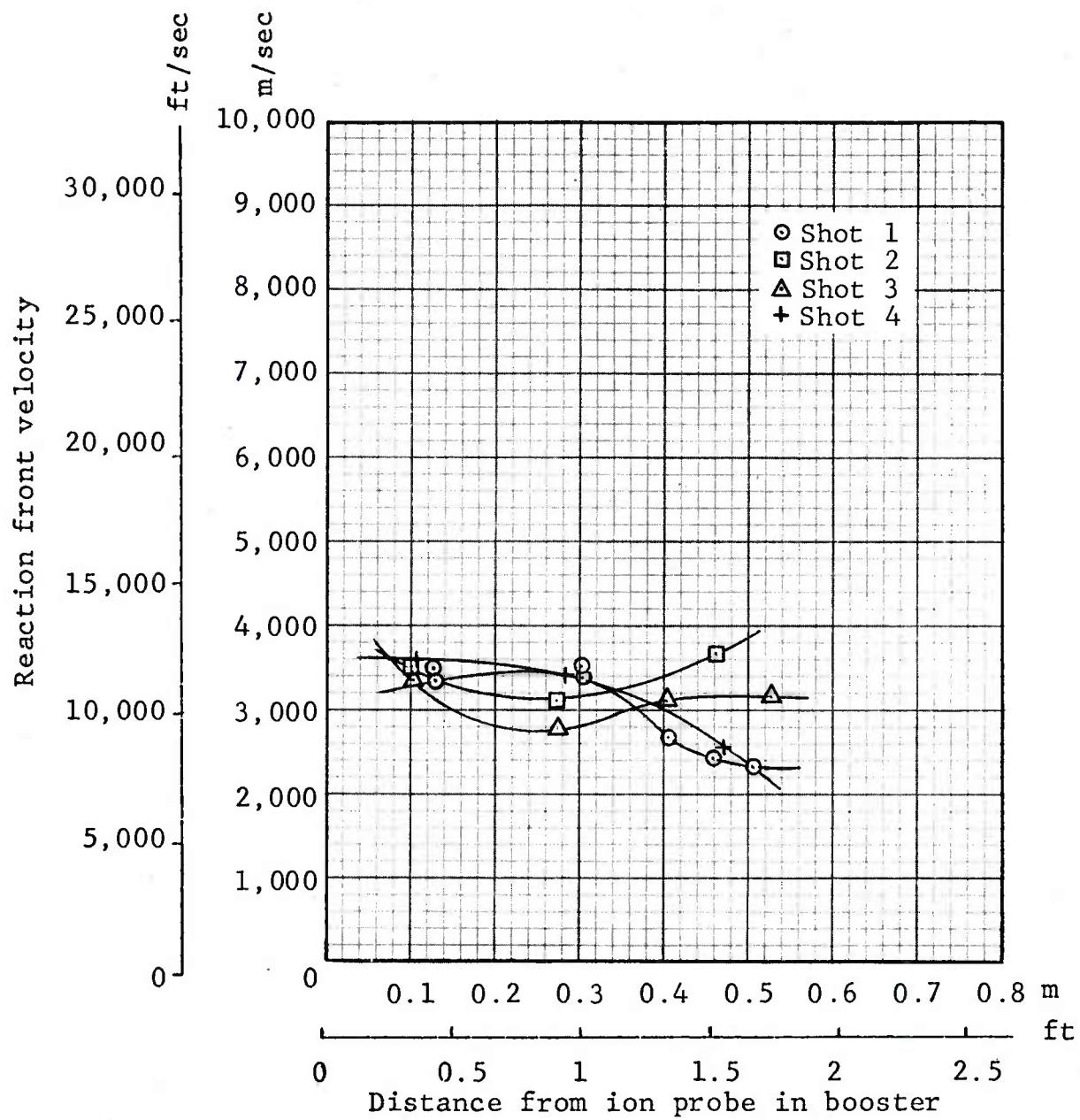


Fig C.5 Test series 5, sellite wash tank, reaction front velocity data

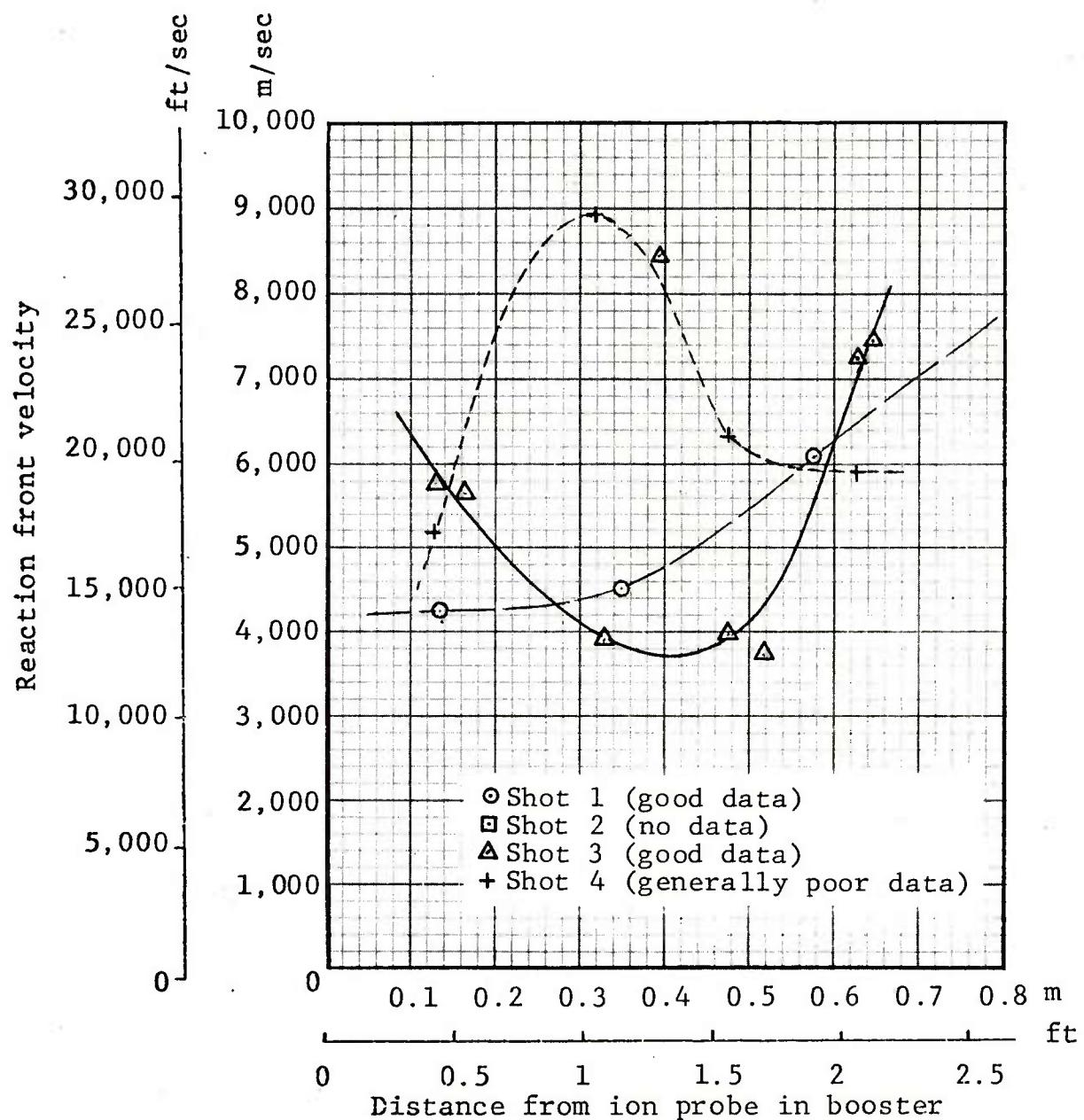


Fig C.6 Test series 6, nitrator 4, reaction front velocity data

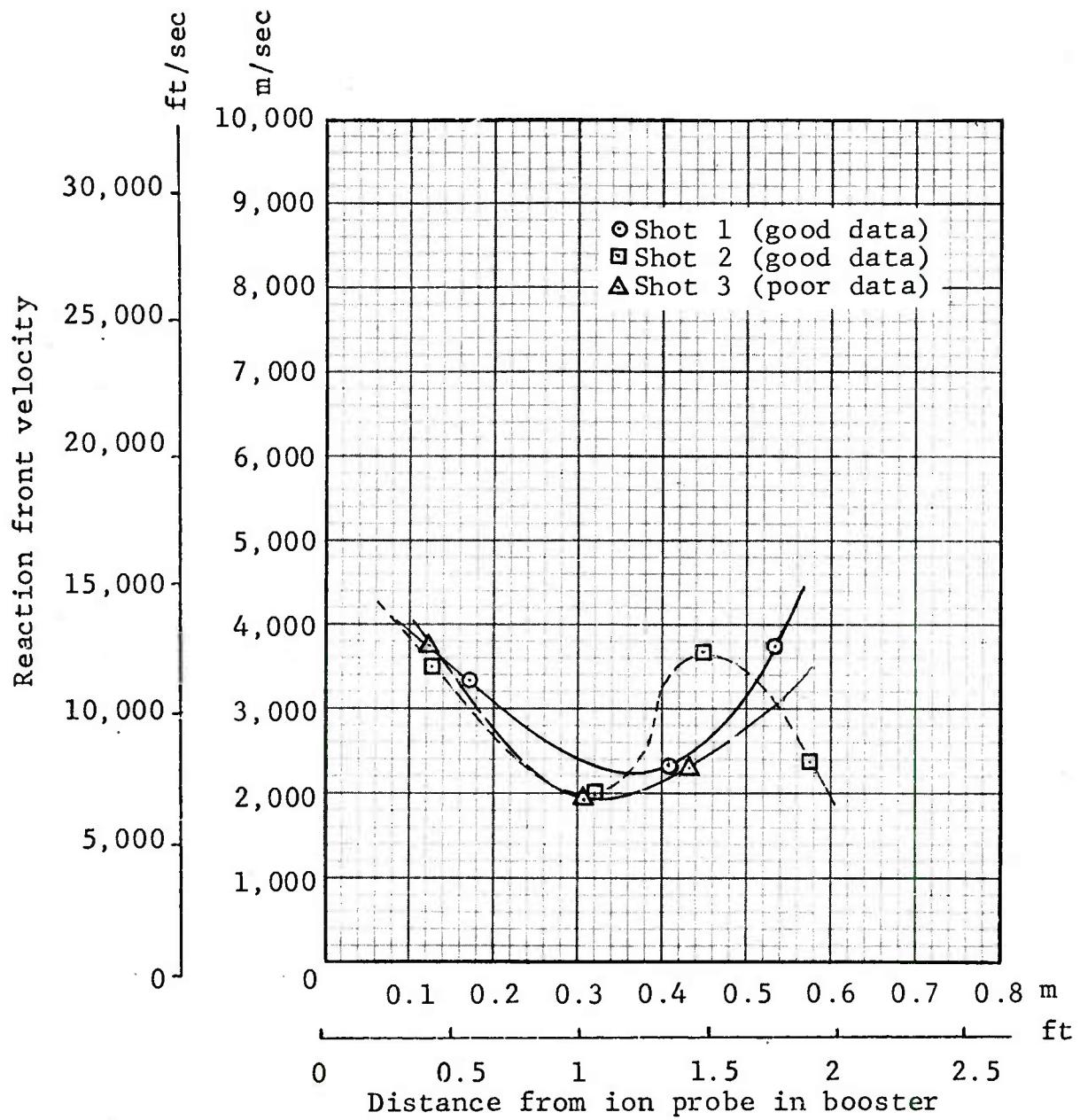


Fig C.7 Test series 8, nitrator 8, reaction front velocity data

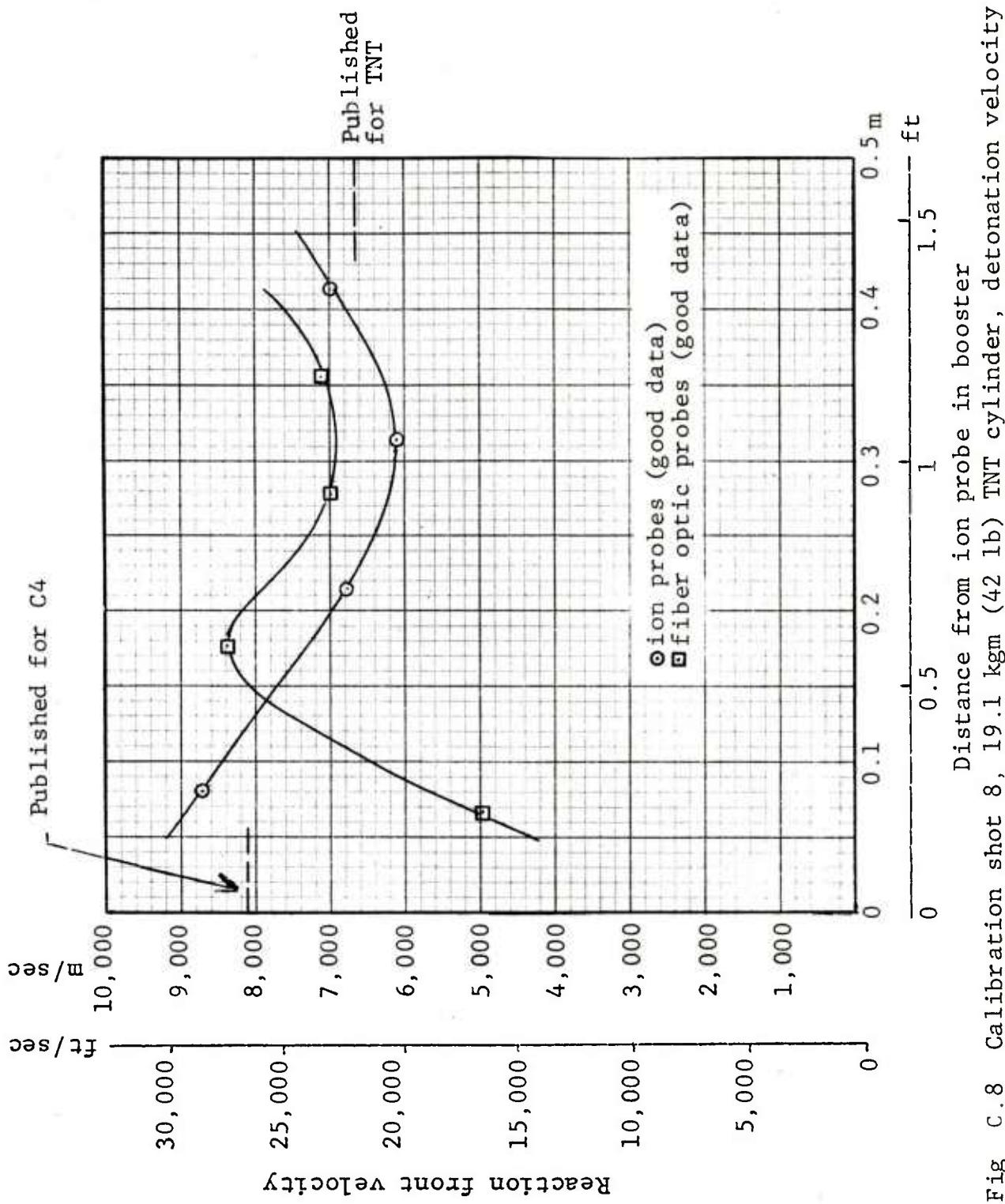


Fig C.8 Calibration shot 8, 19.1 kgm (42 lb) TNT cylinder, detonation velocity data

APPENDIX D
PHOTOGRAPHIC SUMMARY OF THE PROJECT

To help clarify the discussions in the main body of the report, a photographic summary of the project has been prepared. This shows the assembly of a typical small-scale nitration reactor, components tested in the field at the IITRI test site, and setup and results from a large-scale reactor at the National Space Technology Laboratories facility.

Figure D1: System Components

A typical model nitration reactor (nitrator 3A) is shown disassembled. The components are (from left to right): DNT drop tanks, draft tube and cover assembly, reactor tanks, and heat transfer coils.

A pipe reducer and solenoid are set on the 19 liter (5 gallon) can. The reducer screws onto the bottom of the can and the solenoid valve screws onto the reducer. Liquid DNT is poured into the can and remains there until the solenoid is opened.

Just above the DNT drop tank in the photograph is a light sensor box for the fiber optic probes.

An ion probe is set on the cover. The probe consists of pairs of fine wires terminating at different lengths inside a glass tube. The glass protects the wires from the acid in the tank. The ion probe is inserted through the cover along the inside wall of the draft tube. The 45 deg angle pipe in the cover is for routing the DNT into the draft tube from the DNT drop tank assembly.

An agitator assembly is laying on the tank. The agitator shaft is inserted into the draft tube through the cover. A small magnet is attached to the coupler between the shaft and the air motor. This magnet triggers a magnetic field sensitive switch each revolution of the shaft so that rpm can be monitored.

Six concentric coils are hung inside the tank between the tank wall and the draft tube. The coil windings are distributed so that the spacings between adjacent wires give a scaled coil height simulating the real system. Two thermocouples are laying on the largest coil. These are inserted into the tank to record chemical mixture temperature during the tests.

Figure D2: Draft Tube Assembly and Tank with Coils

A model nitration reactor is shown partially assembled. The six coils have been inserted into the tank and the two thermocouples are in place. The draft tube and cover assembly has been instrumented and is ready for insertion into the tank. An ion probe is wired in place on the outer wall of the draft tube for this particular shot. Fiber optic probes are epoxied into three holes in the draft tube wall pointing inward.

Figure D3: Thermocouple locations in Tank

One long thermocouple was positioned near the tank bottom so that its tip was near the center of the tank below the draft tube. A second thermocouple was positioned about halfway up the tank wall.

Figure D4: Draft Tube Assembly with Fiber Optic and Ion Probe Epoxied in Place

Four fiber optic probes are shown epoxied facing inward into the draft tube (left side of tube in picture). An ion probe can be seen positioned along the inside draft tube wall and epoxied to the cover. The 45 deg pipe for directing DNT into the draft tube is also shown.

Figure D5: DNT Drop Tank and Solenoid (Upside Down)

The DNT drop tank assembly is shown with a heating tape wrapped around the tank bottom and the pipes leading to the reactor. The heating tape was used to help prevent crystallization of DNT in the tank and plugging of the pipes.

Figure D6: Booster and Wooden Stand Positioned on Steel Witness Plate

A cylindrical (length to diameter ratio of 1) C-4 explosive booster was used in each test. The safest and most direct contact in all nitrator and wash tank shots was obtained by positioning the booster at the bottom of the tank. For separator shots, the booster was positioned at one end of the rectangular box at the level of the liquid TNT layer. For boosting at the tank bottom, a wooden stand was required to position the tank above the booster. The wooden stand and booster sat on a steel witness plate.

Figure D7: Tank Positioned in Field

A reactor is shown positioned on its wooden stand in the field. The reactor was located at the intersection of two perpendicular blast lines each containing six or seven

pressure transducers. The northward blast line is shown in the picture behind the tank. The DNT drop tank is in place on top of the test reactor. For tests not requiring DNT, no drop tank was used.

Figure D8: System Insulated in Field

A reactor is shown ready for testing. Insulation was required to minimize heat losses and keep the chemicals liquid and at the temperatures present in the real TNT manufacturing facilities. The hot/cold water hose is shown leading to and from the coils at manifolds. An air hose was buried with the water hoses up to the reactor to provide air for the agitator motor.

Figure D9: Pouring Liquid TNT into Tank

Once the component was positioned in the field, insulated, instrumented, filled with acid, and heated above the melting point of TNT, a predetermined amount of liquid TNT was poured into the tank.

Figure D10: Pouring Liquid DNT into the Drop Tank

For reactor shots requiring DNT, liquid DNT was poured into the drop tank. Later, the drop solenoid valve was opened allowing DNT to enter the reactor tank. The DNT reacted with the acid for a predetermined time before detonation was initiated.

Figure D11: Acid Wash Tank Compartment

An acid wash tank compartment is shown during final preparations in the field. This metal box contained a draft tube, agitator, and a single heat transfer coil in contact with the draft tube. The setup represented the inlet mixing compartment of the 10-chamber acid wash tank.

Figure D12: Separator Tank

A separator tank is shown with a removable heating coil and agitator in position in the cover of the tank. Once the acid was heated, liquid TNT was poured into the tank and agitated for about 1 hr. About 10 min before initiation, the coils and agitator were pulled from the tank and protected in a nearby hole. The chemical mixture was allowed to settle during the 10 min period just prior to detonation.

Figure D13: Typical System Damage, without Detonation

When a system did not detonate, large segments of the system remained after the test, the crater size was quite small, a clean hole in the witness plate resulted from the booster alone, and unreacted liquid was evident in the field. In fastex moving pictures of such shots, the reactor could be seen being rocketed into the air and thrown out of the field of view.

Figure D14: Typical Witness Plate Damage after a Detonation

When a detonation occurred, almost no evidence of the system could be found after the test, the crater was generally large and the witness plate was either as shown in the picture or broken into several pieces. Generally circular gouges were seen surrounding the hole in the center of the plate. When detonation occurred, a white flash generally "bleached out" several frames of fastex film running at about 4000 frames per sec.

Figure D15: Witness Plate Damage for Separator Detonation

The last two separator shots were quite spectacular. The witness plate (two adjacent plates were used per shot) were broken into several large fragments, some of which were thrown up onto the cement blast lines.

Figure D16: Crater from Separator Detonations

The craters formed from the last two separator detonations were quite large (about 3.35 m (11 ft) diameter by 1.52 m (5 ft) deep). These were the largest craters observed in the small-scale tests.

Figure D17: Solid TNT Cylinder, Detonated for Direct Comparison with Nitration Reactors

The damage, TNT equivalencies, and detonation velocities produced by several of the nitration reactors were quite severe. To help isolate the contributions of geometry and chemical composition, a solid TNT cylinder of approximately the length to diameter ratio of the reactors was constructed and initiated with a C-4 booster on the bottom exactly as the reactors were initiated. It was instrumented with ion and fiber optic probes.

Figure D18: TNT Cylinder Witness Plate

The witness plate positioned below the solid TNT cylinder was dished somewhat and punctured with a hole due to the booster in contact with the plate. The crater was quite small -- about 0.2 m (8 inches) deep by 1.22 m (4 ft) wide.

Figure D19: Setup at NSTL

Large-scale shots (90.8 kg (200 lb) of nitrobody) were set up at the NSTL to evaluate size scaling for the various components. Here, the hot/cold water system is being installed.

Figure D20: Mock Reactor in Position Under Removable Sled at NSTL

The reactor was positioned in the field beneath two steam kettles. The steam kettles were for melting TNT and DNT remotely in the field. The kettles were mounted on a sled with a steam generator and water supply. When the TNT and/or DNT were in the liquid state, they were dropped into the reactor by opening solenoid valves. The sled was then pulled by a truck to a steel building 61 m (200 ft) from the blast pad prior to initiation.

Figure D21: Nitrator 8 Positioned under Melt Kettles in Field

This view shows the hot/cold water hoses leading to the reactor coils, a plastic tube used for acid transfer to the reactor, and the flexible hoses leading from the steam kettles down to the reactors.

Figure D22: Nitrator 8 (90.8 kg (200 lb) of TNT at NSTL) Witness Plate Damage

The witness plate damage and crater produced by the large-scale nitrator 8 shot was quite similar to the small-scale shots at the IITRI Indiana test site (see figure G13).

Figures D23 and D24: Nitrator 8 Cover and Draft Tube Assembly and Coil Remains (90.8 kg (200 lb) TNT at NSTL)

Large segments of the system components were found after the tests. This is again quite similar to the small-scale test results (see figure D13).



Fig D.1 System components

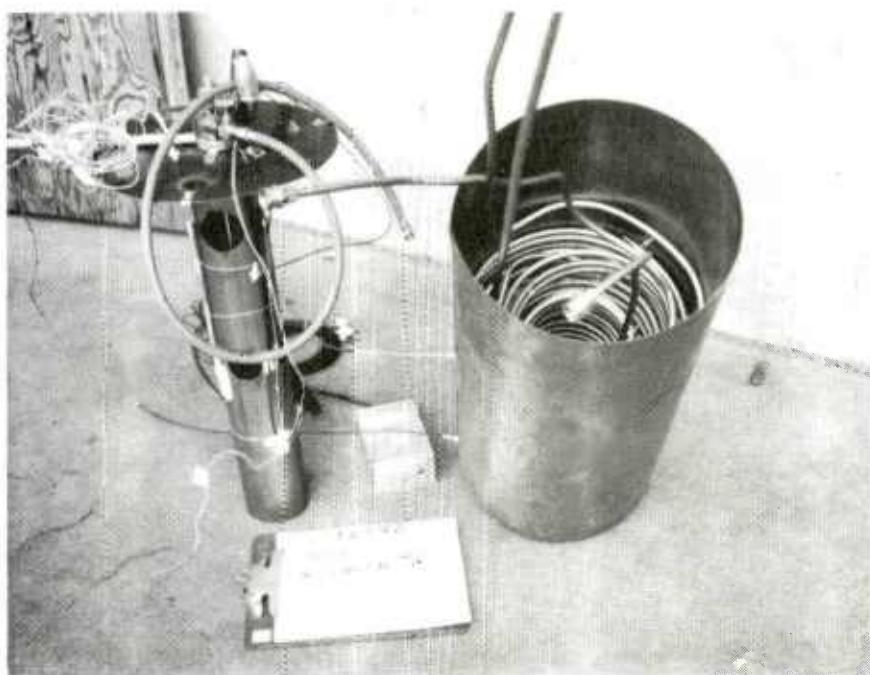


Fig D.2 Draft tube assembly and tank with coils



Fig D.3 Thermocouple locations in tank

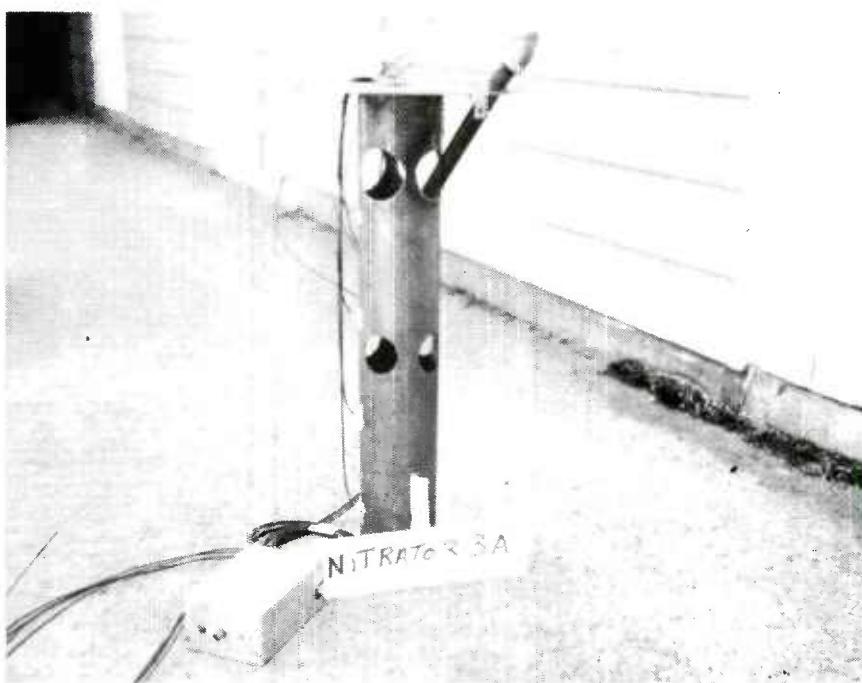


Fig D.4 Draft tube assembly with fiber optic and ion probes epoxied in place



Fig D.5 DNT drop-in tank and solenoid (upsidedown)

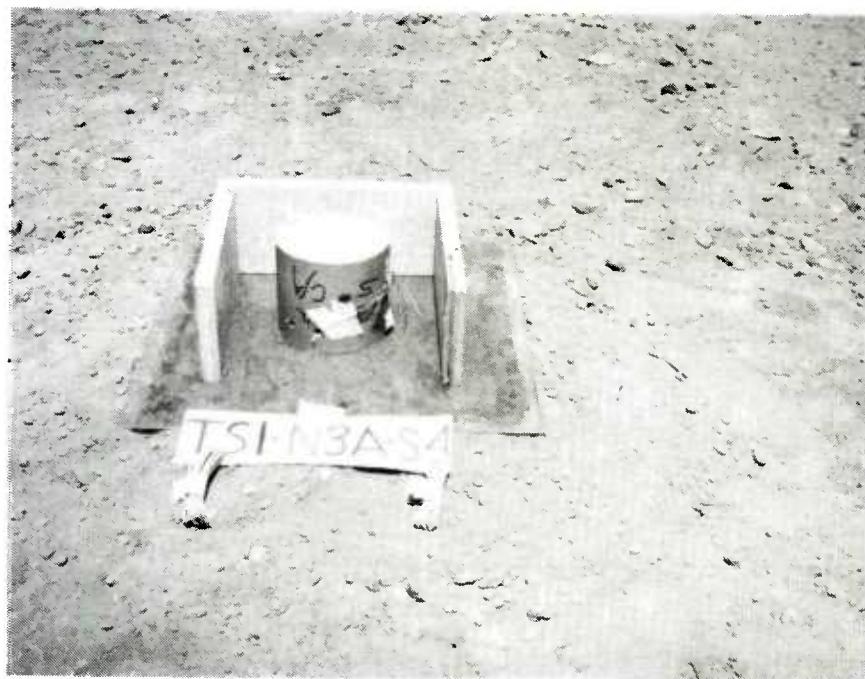


Fig D.6 Booster and wooden stand positioned on steel witness plate



Fig D.7 Tank positioned in field

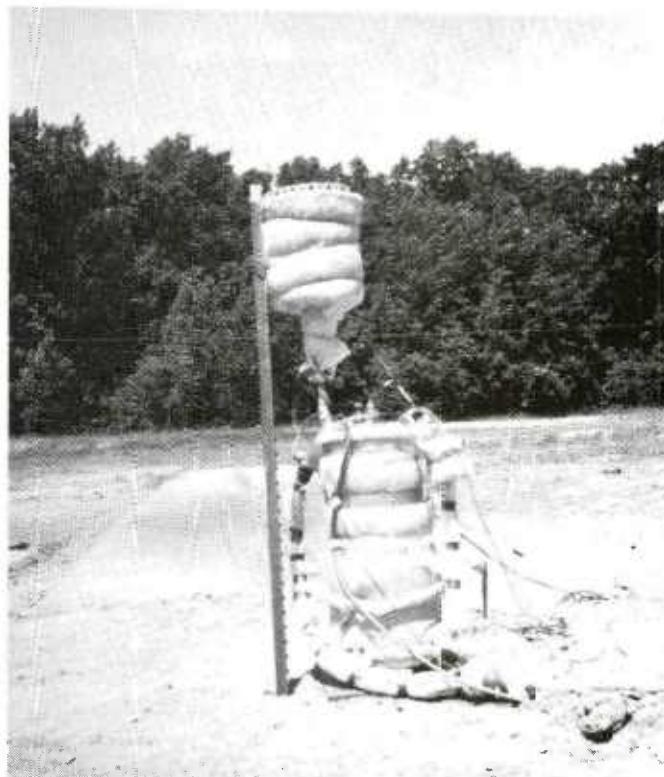


Fig D.8 System insulated in field



Fig D.9 Pouring liquid TNT into tank



Fig D.10 Pouring liquid DNT into the drop tank

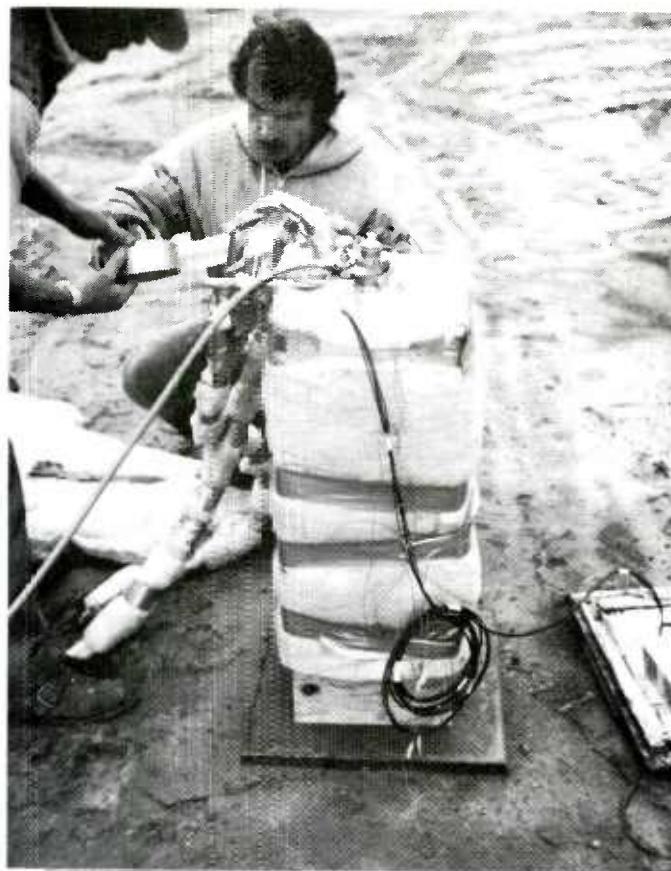


Fig D.11 Acid wash tank

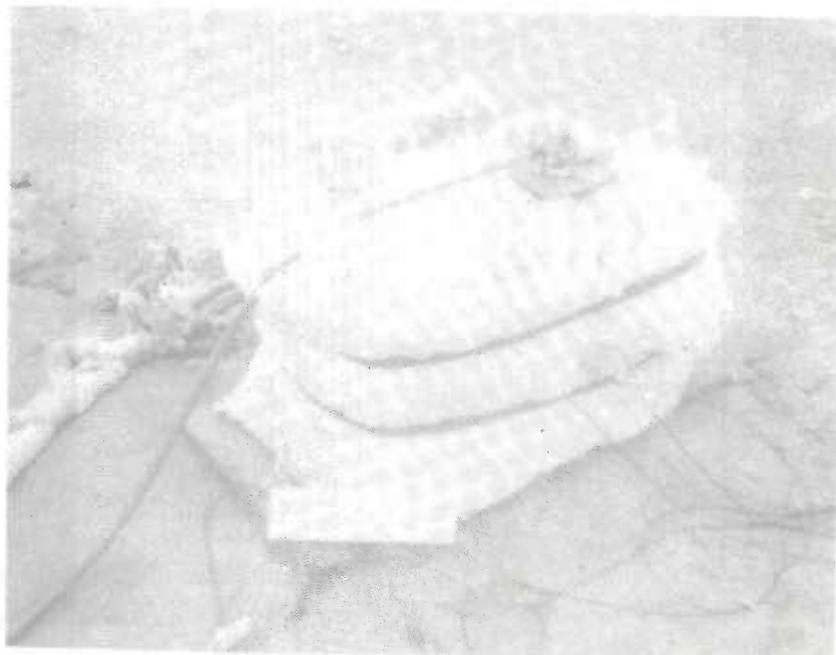


Fig D.12 Separator tank position

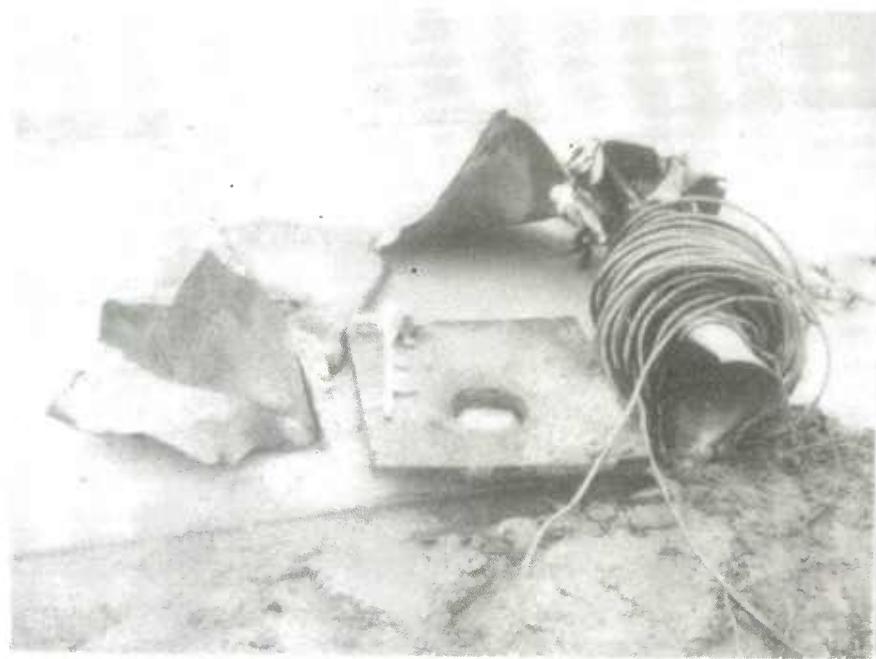


Fig D.13 Typical system damage, without detonation



Fig D.14 Typical witness plate damage after detonation



Fig D.15 Witness plate damage for separator detonation



Fig D.16 Crater from separator detonation (broom handle is 1.35 m (4.4 ft) long)

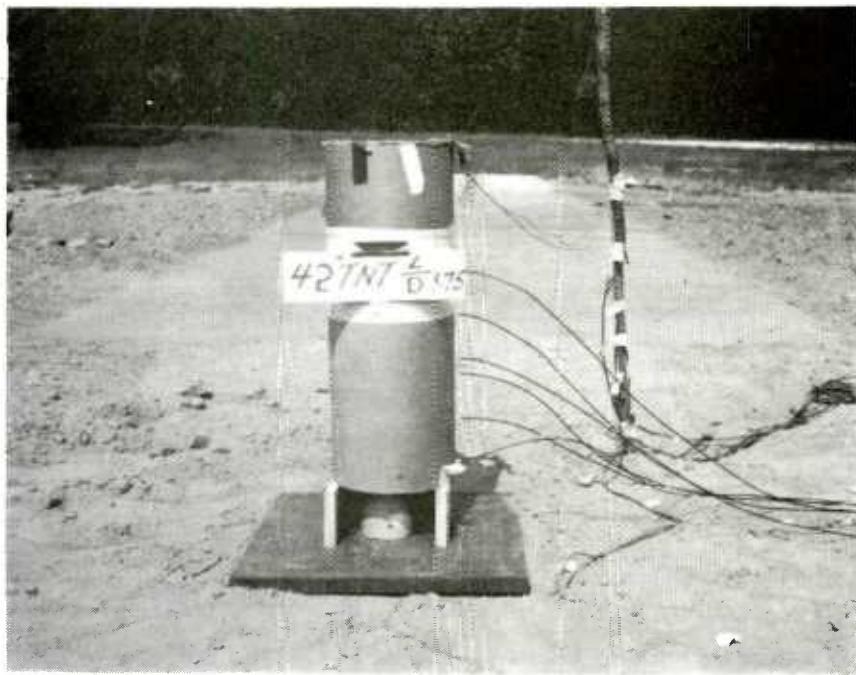


Fig D.17 Solid TNT cylinder detonated for direct comparison with nitration reactors



Fig D.18 TNT cylinder witness plate damage



Fig D.19 Setup at NSTL

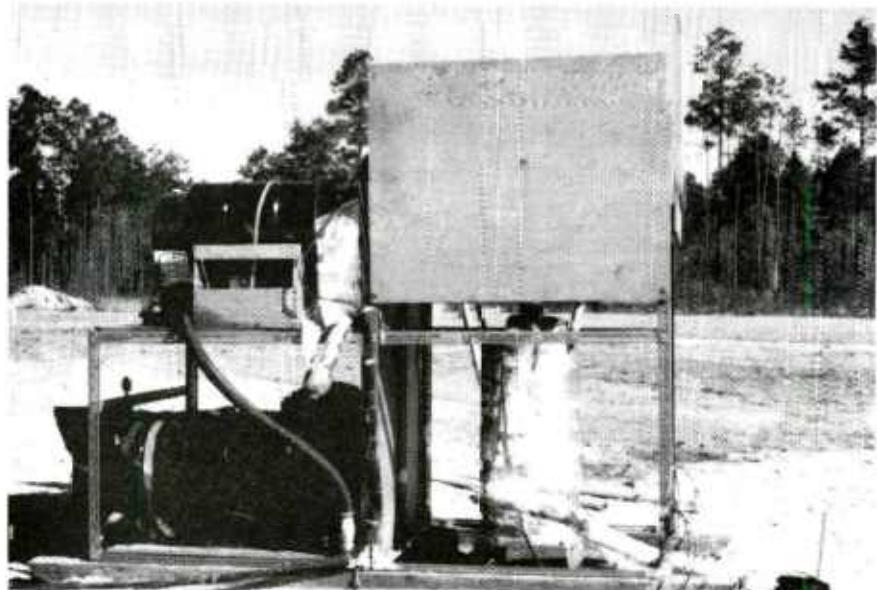


Fig D.20 Mock reactor in position under removable shield at NSTL

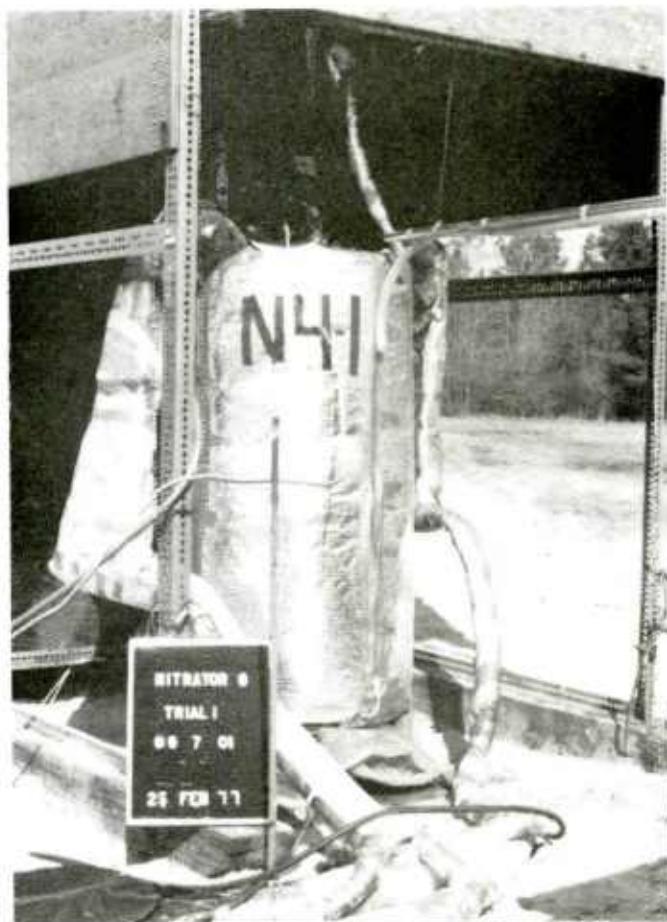


Fig D.21 Nitrator 8 positioned under melt kettles in field

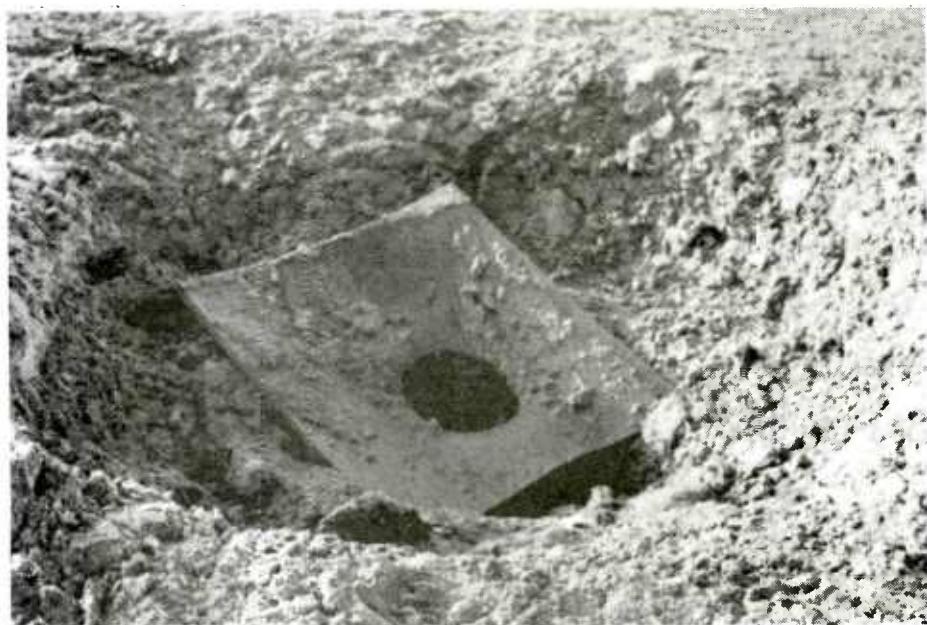


Fig D.22 Nitrator 8 witness plate damage and crater (90.8 kg (200 lb) of TNT at NSTL)



Fig D.23 Nitrator 8 cover and draft tube assembly remains
(90.8 kg (200 lb) of TNT at NSTL)

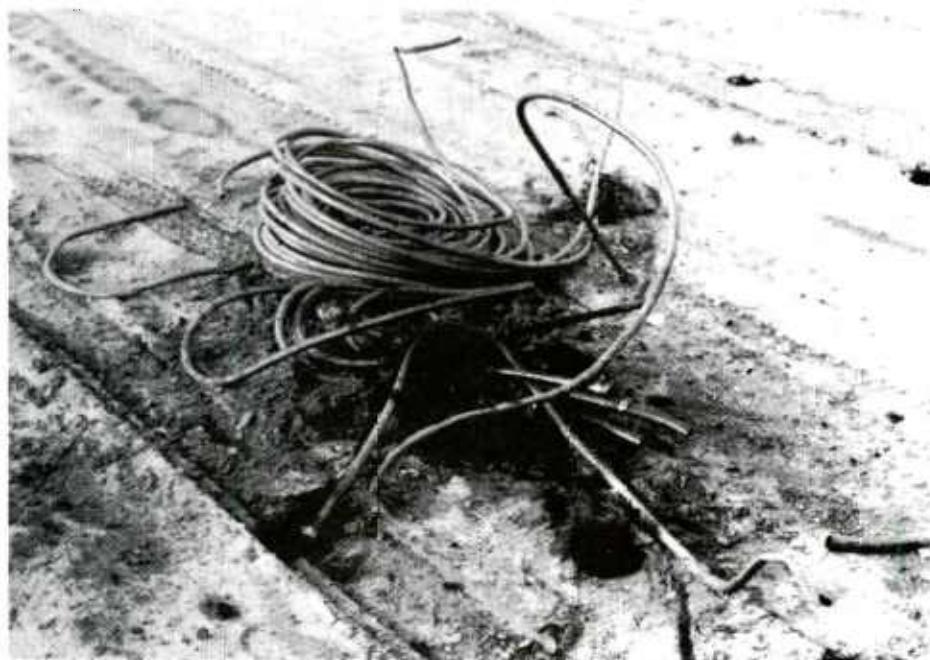
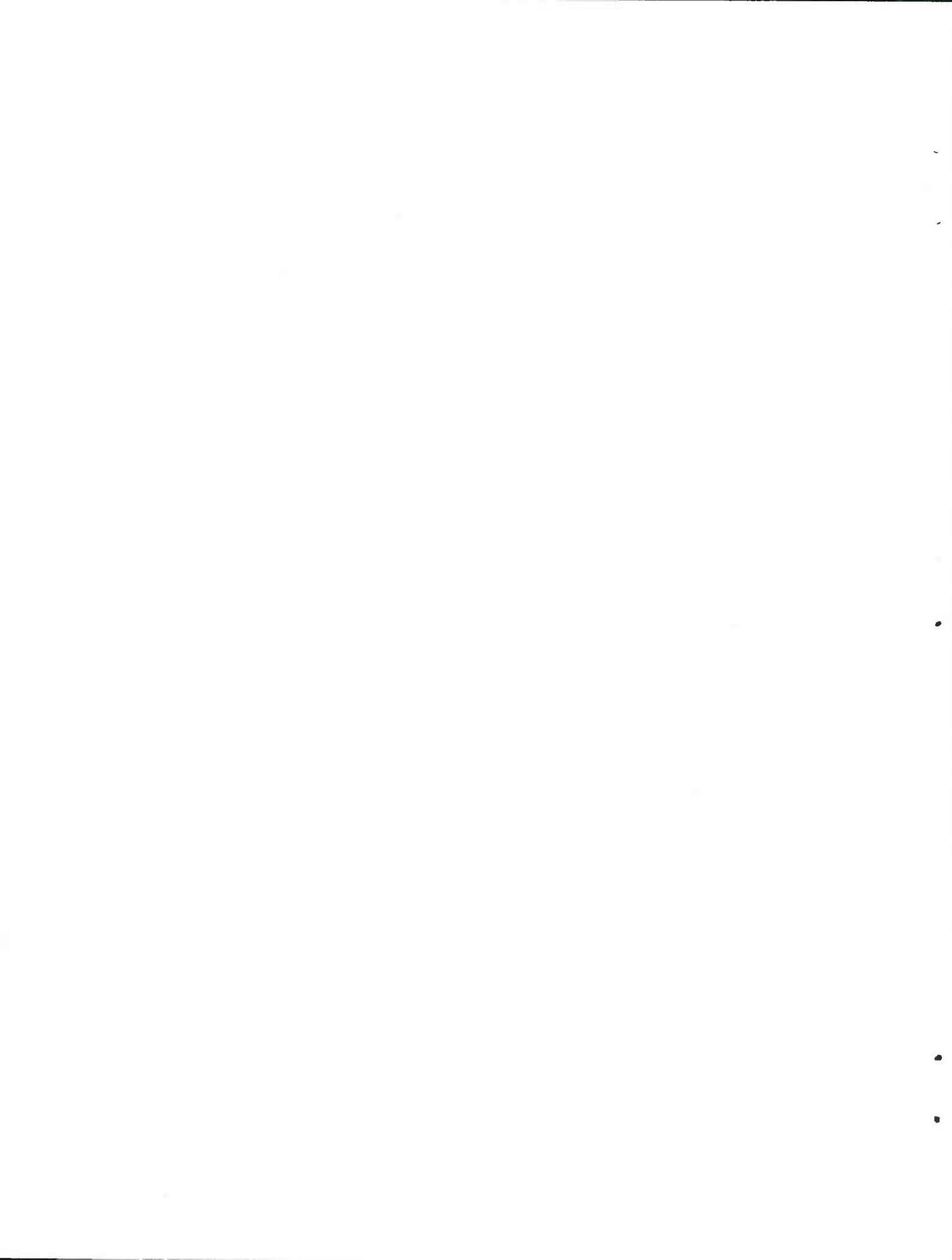


Fig D.24 Nitrator 8 coil remains
(90.8 kg (200 lb) of TNT at NSTL)



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